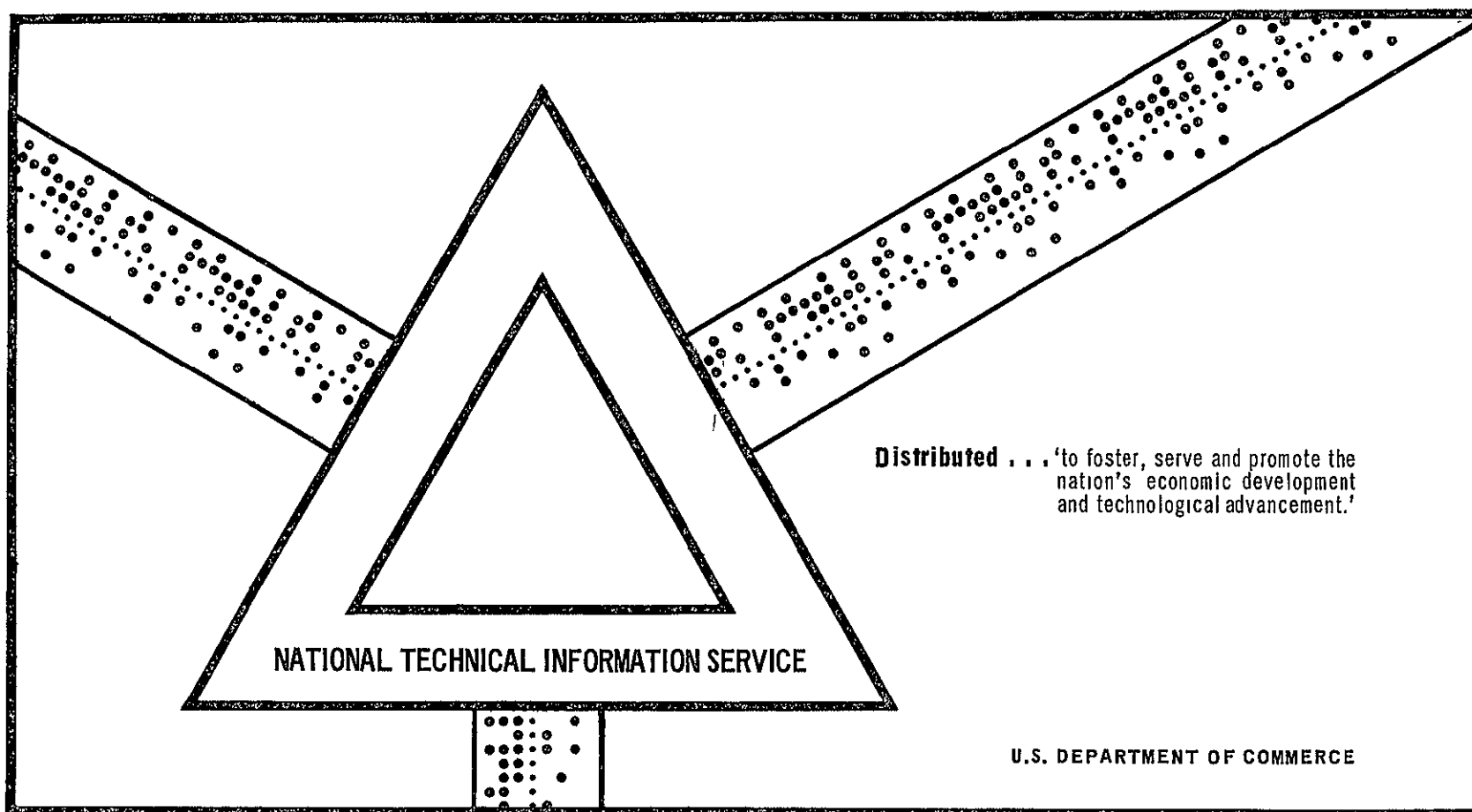# FLUID BALANCE IN ARTIFICIAL ENVIRONMENTS: ROLE OF ENVIRON-MENTAL VARIABLES

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FLUID BALANCE IN ARTIFICIAL
ENVIRONMENTS: ROLE OF
ENVIRONMENTAL VARIABLES

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PREFACE

The question of the need for maintaining an adequate humidity in the atmosphere is one that has been of concern to engineers, physicians and physiologists since the first artificial environment was established. While much data have been collected regarding various aspects of the problem, few experiments have been conducted in which the total impact of the environment on crew physiology and comfort have been studied. The research reported here summarizes an extensive series of experiments relating the environment to physiological insensible water loss and crew comfort. The results should be of practical importance in the design of systems requiring humidity control.

The authors wish to express their appreciation to the many individuals in the USAF School of Aerospace Medicine that contributed to the conduct of this study.

B. E. WELCH, Ph.D.

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LIST OF SYMBOLS[1]

BSA	Body surface area
GC	Atmospheric gas composition
IWL	Insensible water loss
IWL_G	Metabolic insensible water loss
IWL_R	Respiratory insensible water loss
IWL_S	Skin insensible water loss
IWL_T	Total insensible water loss
P_B	Barometric pressure
P_{H_2O}	Water vapor pressure
T_a	Ambient temperature
T_{bg}	Black globe temperature
T_{ew}	Effective wall temperature
T_s	Average skin temperature
V	Wind velocity
W_e	Skin insensible water loss
W_R	Respiratory water loss
W_{T_i}	Light thermal sweating
W_M	Emotive sweating
W_D	Diffusional water loss
W_G	Weight loss through metabolic gas exchange

W_A	Initial weight of subject
W_I	Total intake (liquid and solid)
W_0	Total output (liquid and solid) except W_e
W_Z	Final weight of subject
W_{O_2}	Weight of oxygen in expired air
W_{CO_2}	Weight of carbon dioxide in expired air
W_{ms}	Weight change on metabolic scale
W_{ig}	Weight of water vapor in the inspired gas
W_{e_1}	Direct measure of skin insensible water loss
$W_{e_{1_t}}$	Total skin IWL by direct measurement
$W_{e_{2_t}}$	Total skin IWL by indirect measurement
W_{dr}	Weight of the Drierite canister
W_{R_t}	Total respiratory water loss (in grams) per experiment
W_T	Thermal sweating
W_{T_s}	Thermal sweating composed of sensible eccrine activity
W_{T_i}	Thermal sweating composed of insensible eccrine activity

[1]Other symbols, applicable only to specific equations, are defined in context.

FLUID BALANCE IN ARTIFICIAL ENVIRONMENTS:
ROLE OF ENVIRONMENTAL·VARIABLES

I. INTRODUCTION·

Natural environments which feature extremes of temperature and relative humidity are not unfamiliar to man, although the more remarkable extremes are usually found in desert or arctic climates, where populations are small and dispersed. With the ever-increasing utilization of environmental engineering to provide artificial climates in human habitations and transport vehicles, the specific influence of environmental parameters upon health, comfort, and performance has assumed greater significance. With the ability and technology to control his environment, man must understand the physiologic ·and metabolic consequences of the microclimates that he has created.

Whereas relative humidities below 25% are rarely experienced for a sustained period in the climate of the temperate zone, indoor heated air may be dried in winter to a relative humidity below 20% day after day. Also, the pressurized cabins of commercial jetliners sometimes produce relative humidities below 10% when the plane has reached cruising altitude. Extremes of dryness have become an accepted part of indoor life--accompanied by a general ignorance or disregard for consequences to health and performance.

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In the design of any sealed environmental system--such as an

aircraft cabin, spacecraft cabin, or hospital isolation unit--

temperature, humidity, wind speed, total barometric pressure, and

atmospheric gas composition all play a critical role, not only in

human ecology, but also in the satisfactory operation of technical

equipment and life-support systems. While excesses of water vapor

may condense and freeze on cold valves, oxygen lines, and instrument

gages; diminished water vapor pressures may lead to marked discomfort

to personnel and unsatisfactory performance levels (121, 123).

Excessive temperatures will lead to heavy thermal sweating and an

overloading of air-conditioning or life-support systems; while

low temperatures will lead to increased metabolic rates, general

discomfort, and a significant performance deficit.

Water and thermal balance in artificial environments are,

therefore, problems which encompass the full spectrum of human

habitats--from the home and office, to the commercial airliner,

to the deep-space vehicle. For each of these habitats it is most

important to understand the direct influence of each environmental

variable upon fluid balance and upon subjective and objective

tolerance to the environment.

It is the aim of this paper to investigate the role of the

most critical environmental parameters--ambient temperature (T_a),

water vapor pressure (P_{H2O}), total barometric pressure (P_B), wind

velocity (V), and atmospheric gas composition (GC)--from three

important aspects of human survival and function in artificial environments:

1. Insensible water losses and their skin, respiratory, and metabolic components.

2. Overall fluid and weight balance, and routes of fluid intake and output.

3. Development of signs and symptoms related to environmental intolerance.

Each of these three areas will be explored and discussed in terms of the ambient parameters which most influence them and in terms of their relationships to each other. The possible mediating roles of other environmental or physiologic variables will also be reviewed.

II. SUMMARY

Considering the results and conclusions of this study, together with the observations and conclusions of other investigators, one may draw the following picture of insensible water loss and of water balance in artificial environments:

1. In the absence of thermal sweating, skin insensible water loss has two significant components: W_D and W_M.

2. W_D results from movement of water in liquid or vapor form through the epidermis, and its rate is dependent upon both the rate of diffusion through the epidermal water barrier and upon the rate of evaporation from the skin. Either step can be rate-limiting.

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3. W_M results from the diffusion and evaporation of water from eccrine and apocrine sweat glands. Most of this water is actively secreted, but some may also diffuse passively from the ducts.

4. From experiments with subjects who are congenitally devoid of sweat glands or who have had them chemically inactivated, it is clear that W_D is the major component of skin insensible water loss.

5. Five environmental factors---ambient temperature (T_a), total barometric pressure (P_B), water vapor pressure (P_{H_2O}), wind velocity (V), and gas composition (GC)--exert a significant influence upon the rate of IWL_S.

6. The effects of P_B and of P_{H_2O} on IWL_S rates are inversely related over the range studied. There appears to be no interaction between these two variables.

7. The effect of T_a is directly related to IWL_S at low P_B, but not as linear at ground level. There is evidence of a strong interaction between T_a and P_B in the determination of IWL_S rates.

8. The effect of GC on IWL_S is evident when helium is substituted for nitrogen at 258 mm. Hg P_B. A significant reduction in IWL_S rates occurs in the He environment. This reduction may be related to the increased thermal conductivity of He and the resulting increased convective heat loss.

9. The effect of V is complex and may be mediated by changes in skin temperature and convective heat loss. A direct relationship with rates of IWL_S exists in the range tested, but at higher values

of V, the influence of changes in P_B and P_{H_2O} are diminished. An interaction between V, on the one hand, and P_B and P_{H_2O}, on the other, is evident.

10. Skin temperature appears to mediate, in part, environmental influences on the rates of skin insensible water loss. T_S correlates closely with changes in T_a and with the effective wall temperature (T_{ew}).

11. Of all environmental measurements considered, rates of IWL_S correlated best with T_{ew}, which provides a determination of the total heat load on a subject.

12. The indirect calculation of IWL_S (W_{e_2}) yields results which are consistently higher than those obtained through the direct measurement (W_{e_1}). The indirect measurement can provide an approximation of skin water losses, but is far from being precise.

13. Intrasubject variation in IWL_S measurements under identical ambient conditions suggests the possibility of some physiologic regulation of insensible water loss rates.

14. Intersubject variations in IWL_S rates are also considerable and may be partially related to differences in epidermal architecture and efficiency of the epidermal water barrier.

15. Respiratory insensible water loss is related to the water-holding ability of the inspired air (i.e., the relative humidity) and to the rate and volume of air that passes through the respiratory tract (i.e., the ventilation rate).

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16. The effect of T_a upon IWL_R is positive but nonlinear, and the effect of P_{H_2O} is negative and nonlinear.

17. Both T_a and P_{H_2O} influence the rate of respiratory water loss by directly altering the R.H. of the inspired air.

18. The effect of P_B upon IWL_R is clearly strong and negative. A reduced total pressure lowers the rate of IWL_R by decreasing pulmonary ventilation.

19. Total insensible water loss is a combination of IWL_S, IWL_R, and IWL_G, and can amount to over 1,000 gm. in a day, even in a relatively comfortable environment.

20. IWL_S forms the major component of IWL_T in all environmental situations tested here and may reach 600 gm./day.

21. Respiratory insensible water loss may contribute up to 44% of IWL_T in an environment featuring a high P_B and a low P_{H_2O}. At reduced P_B and elevated P_{H_2O}, this contribution may fall as low as 26%.

22. IWL_G is relatively constant under the environmental conditions studied here and always formed a very small part of IWL_T, usually less than 8%.

23. Environmental factors such as P_B, P_{H_2O}, and T_a all exerted a significant influence upon weight balance and routes of fluid loss even within the "comfort zone."

24. The effect of changes in gas composition on fluid balance was small, but trends were evident.

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25. The rate of development and the ultimate severity of signs and symptoms related to the environment are closely dependent upon T_a, P_{H_2O}, and P_B, with some dependence upon gas composition as well.

26. Signs and symptoms tend to develop more rapidly at reduced P_B and to reach a more severe level for a given T_a and P_{H_2O}. At 700 mm. Hg P_B, signs and symptoms increased rapidly only below a P_{H_2O} of 6.5 mm. Hg; while at 258 mm. Hg P_B, a rapid increase in signs and symptoms occurred below a P_{H_2O} of 9 mm. Hg.

27. Signs and symptoms are slightly more exaggerated in 100% O_2 and slightly reduced in a He atmosphere, but these changes are not statistically significant.

28. Signs and symptoms develop most rapidly during the first 12 hours of exposure and continue to progress through the first 20 hours of exposure.

29. After the first 20 to 24 hours of exposure, signs and symptoms tended to plateau with no increase in severity and no evidence of improvement. There is no indication of adaptation or acclimatization to the drier environments in the 48 hours of exposure.

30. The nose area showed the most frequent occurrence of symptoms; followed in decreasing frequency-severity by the lip, pharynx, eye, mouth, and tongue areas.

31. The lips exhibited the most frequent development of signs; followed by the eyes, nose, tongue, pharynx, and mouth.

32. Skin, scalp, and general signs and symptoms were least reported and were least severe in exposures no longer than 48 hours.

33. Development of both signs and symptoms in the experimental subjects correlated closely with the rates of skin insensible water loss and total insensible water loss in different environments.

34. Significant variations in skin insensible water loss, respiratory insensible water loss, total insensible water loss, overall weight and fluid balance, and sign and symptom development can be observed when environments within or very close to the accepted "comfort zone," are used. Extreme ambient conditions are not necessary.

35. The qualitative and quantitative analysis of routes of insensible water loss from the human body, as influenced by environmental variables, can be correlated with fluid balance and comfort-performance indices to provide a more complete picture of man's interaction with his environment.

III. BACKGROUND

Evaporative water losses from the human skin and respiratory tract provide the major mechanism of temperature regulation and heat dissipation in warm environments. In these environments the major component of evaporative water loss is provided by the active secretion of fluid by the sweat glands. The rates of sweat production may reach several liters a day and are dependent upon thermal stimuli acting both centrally (hypothalamic) and peripherally (skin sensors) (7, 8, 11, 12).

Even in environmental situations where sweat glands are

not active, however, evaporative water loss from the body surface

continues to take place. Observations on subjects congenitally

devoid of sweat glands (72, 100, 109), and more recently on subjects

whose sweat glands were chemically inactivated (14, 27, 95, 119),

have revealed a significant and continuous loss of water through the

skin--a loss which is entirely independent of active sweat production.

This skin water loss forms a major component of the difficult-to-measure

body water loss which was first termed by Sanctorius in 1614

"insensible perspiration" (4). This phrase encompassed nonsweat skin

water losses, respiratory water losses, and a small metabolic weight

loss created by the slightly excess weight of carbon dioxide exhaled

over the weight of oxygen absorbed. Previous measurements have shown

that 30 to 40 gm./hr. of water may be vaporized as insensible perspira-

tion, resulting in a heat loss of 20 kcal./hr., or more than 25% of

the total body heat loss.

Since the days of Sanctorius many attempts have been made

to quantify the components of insensible perspiration and to clarify

their relationship to environmental conditions (4, 24, 56, 76, 114, 125).

Major difficulties have been created by differences in terminology

and in measurement technics, which have often resulted in the

accumulation of data which is neither reproducible nor comparable

with other experimental results. A reexamination of the phrase

"insensible perspiration" points to one of the major problems.

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If by "insensible" losses we mean those losses which are not readily observable and are difficult to quantify, then under this category we must place at least five different components (table IB). Each of these components represents material which is lost from the body in a vapor or gaseous state and is, therefore, "not perceptible to the senses." Respiratory water loss (W_R) includes the water vapor added to inspired air during respiration and then lost to the environment with expiration. Light thermal sweating (W_{T_i}) includes the very low levels of eccrine activity related to temperature regulation which occurs at threshold and does not result in fluid accumulation on the skin surface. Emotive sweating (W_M) includes the active secretion from apocrine and eccrine glands on the palms, soles, axillae, and head, which is not related to, nor controlled by, thermal changes. Diffusional, or nonsecretory, water losses (W_D) include direct losses through the skin or skin appendages which are nonsecretory in nature. Metabolic gas exchange accounts for the net weight loss (W_G) resulting from the excess weight of CO_2 which is expired over the weight of O_2 inspired, or $W_G = W_{O_2} - W_{CO_2}$.

Sensible water losses (table IA) include those losses which are easily observed and measured because they occur in the liquid phase: urine, feces, vomitus, drooling, tearing, and significant thermal sweating. This categorization of water losses is a most useful one because it includes all normal types and also provides a practical differentiation of routes and underlying control mechanisms.

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All varieties of insensible water loss would have to be included in a discussion of difficult-to-measure water losses (table IC), but the two groups cannot be considered synonymous because of the partition of thermal sweating into both the "insensible" and the "sensible" water-loss categories.

The determination of the rates of total insensible water loss and its components is largely dependent upon the technics of measurement. If a skin-capsule method is used to determine skin water loss, then only the W_D component (assuming no thermal sweating) is measured if the capsule is placed on the abdomen or back, or the W_D plus the W_M components if the capsule is placed on the palm or forehead. Using this capsule technic, one can only roughly extrapolate the actual total-body skin water loss from data derived from localized areas. In the same way the localized measurements of skin water loss rates are difficult to relate to a determination of total insensible water loss.

Using the whole-body gravimetric technic, however, one is immediately provided with a summation of all routes of insensible weight loss including W_D, W_M, W_G, and W_R (fig. 1). By collecting and measuring W_R and W_G, one can then determine the actual total-body rate of skin water loss (W_e) and isolate all the components of IWL_T. While this technic is most suitable for obtaining a picture of the rates of total insensible water loss with its skin (IWL_S), respiratory (IWL_R), and metabolic (IWL_G) segments (fig. 1), it provides no information concerning regional variations in water loss rates.

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Because the objectives of this investigation are related

to overall water balance in artificial environments and to the

interaction of ambient variables with rates of sensible and

insensible water losses, the whole-body gravimetric technic, was

selected over the capsule procedure. In addition to the direct

measurement of skin insensible water loss, a derived or indirect

calculation of this loss, utilizing a complete weight-balance

equation, was also undertaken (see table IC and Methods).

Of all the categories of difficult-to-measure water losses,

skin insensible water loss has been the most formidable in terms

of direct and accurate measurement and in terms of the determination

of the exact mechanisms involved (32). Previous measurements of

IWL_S have involved more than two dozen separate investigators,

multiple anatomical sites, and at least seven different experimental

technics (table II).

Beginning with Ikeuchi's whole-body gravimetric measurements

in 1927 (62) and progressing to Goodman and Wolf's infrared airflow

analysis studies of 1969 (50), measured rates of IWL_S have ranged

from 1.5 (103) to 90.0 gm./m^2/hr. (83), a span of over 60-fold.

Earlier experimental data on skin water loss, such as the

work of Taylor and Marbarger (112), demonstrated a partial

dependence of water loss upon some environmental variables,

especially humidity and air movement. Further studies by Buettner (24),

Hale et al. (56), Hertzman et al. (60), and others (28, 76, 113) showed

variations in water loss rate dependent upon humidity, airflow, temperature, and barometric pressure. However, the direction of these variations and their degree continued to generate disagreement in the literature. As an example, reduced barometric pressure was found by Foa (as cited in Marshall and Specht, 75) and by Guillemard et al. (55) to produce a decrease in skin insensible water loss, while Pi-Suner (98) concluded that reduced P_B had no effect, and Hale et al. (56) and McCutchan and Taylor (76) agreed that reduced P_B significantly increased the rate of IWL_S.

The measurement of IWL_R and of IWL_G has been subject to much less controversy and most investigators have reached general agreement about the rates of water loss and the influence of some environmental variables upon these rates (19, 28, 29, 75, 131).

The direct effects of some environmental variables upon human fluid balance are quite apparent. Large increases in ambient temperature lead to increased evaporative water losses by sweating. Although renal fluid output diminishes as a compensatory measure, water conservation is usually not sufficient to maintain fluid balance, and an increased fluid intake must take place.

Much more subtle alterations in fluid balance may be caused by other environmental alterations, such as changes in P_B. In 1961, Welch et al. (126) observed that experimental subjects living in a space-cabin simulator, with P_B reduced first to 383 mm. Hg and then to 189 mm. Hg, lost considerable weight (an average of 3.25 kg. in 30 days)

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and that this weight loss was accompanied by a considerable loss of total body water. With the advent of manned spaceflight, the combination of reduced barometric pressure, increased oxygen tension, and weightlessness was found to produce significant losses in total body fluid, with fluid loss failing to act as a stimulus for increased fluid intake (47, 48).

In determining 24-hour fluid balance under a wide variety of environmental conditions, all sources of intake and output must be carefully measured. Utilizing a general balance equation (table IC), one can determine IWL_S by an indirect method in which one solves for W_e in the balance equation.

When considering the total fluid output in the 24-hour balance studies, one can look at the contribution of total insensible water loss to the total output and examine the influence of the various environmental parameters in increasing or decreasing this contribution. In a similar manner, one can break down IWL_T into its components of IWL_S, IWL_R, and IWL_G and examine the relative importance of each of these when environmental conditions are varied. Although it has been stated that IWL_S is the greatest contributor to IWL_T (4), it is not clear that this dominance holds for all normally encountered ambient conditions.

The effect of varying environmental parameters upon human health, comfort, and performance has been the subject of serious investigation since 1775 when Blagden (15) studied the effects of

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very hot, dry air on human subjects. Since that time it has been recognized that many ambient parameters--such as water vapor pressure (4, 8, 56, 114), wind speed (109, 113), temperature (24, 44, 113), atmospheric gas composition (40, 59, 127), and total pressure (40, 56, 76)--can directly influence comfort, and that the interaction of these parameters can profoundly influence the rate of onset of signs and symptoms of environmental intolerance (101).

Extremes of ambient temperature will lead to profuse sweating and inordinate fluid loss on the one hand, and to shivering and increased metabolic rate on the other. In either case, performance will diminish. The conventional ASHRAE human-comfort guidelines (2), applicable to subjects sitting still in light clothing, suggest a comfort zone of dry-bulb temperature of 71° to 82° F. This comfort zone is modified only slightly by changes in wet-bulb temperature or relative humidity, so that the ideal comfort temperature is defined as 77° F. with a 30% R.H., and 76° F. with a 90% R.H.

Such comfort guidelines have tended to obscure the importance of water vapor pressure in the environment. Whereas very high P_{H_2O} will effectively prevent adequate human heat dissipation through evaporation and lead to accumulations of water on skin and clothing, very low P_{H_2O} will lead to localized discomfort and impairment of the sensorium (74). The effects of low humidity are primarily localized to those areas directly exposed to the ambient conditions and not protected by keratinized epidermis or epidermal appendages.

Drying of mucous membranes of the nose, mouth, and pharynx is common and is often followed by inflammation. Chapping of the lips is one of the earliest signs of drying, while drying of the eyes can become a serious medical problem, with the development of conjunctivitis, pain, and diminished vision. Skin and scalp drying, with resulting itching and flaking, also present a major problem.

Morning nasal stuffiness during the winter months is a problem familiar to most inhabitants of the temperate zone, and humidifiers have seen increasing use in an attempt to ameliorate this discomfort. American astronauts in the Mercury, Gemini, and Apollo programs have repeatedly complained of nasal stuffiness, mouth dryness, and lip-chapping in their low-humidity environments (85). In this situation, the contributing effects of low barometric pressure and high oxygen tensions must also be considered.

Wind velocity will affect comfort by changing the rates of convective heat transfer and by altering the rate of water evaporation from the human skin (34, 39). Elevated wind velocities will lead to subjective cooling and to increased drying of exposed surfaces.

Gas composition will also affect comfort by altering the heat capacity and thermal conductivity of the surrounding medium. Helium, for example, will be more efficient than nitrogen in removing body heat and will cause greater human heat loss to the environment (13, 40).

Total barometric pressure will influence comfort by altering convective and conductive heat losses and may also change the rates of

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insensible water loss and body heat loss through evaporation (30, 81).
Therefore, reduced barometric pressures may augment the rates of
insensible water loss and lead to signs and symptoms of drying at
water vapor levels significantly higher than those levels which might
cause symptoms at sea level.

IV. METHODS AND PROCEDURES

Environmental studies were conducted in the altitude-chamber
complex located in the Environmental Systems Division of the USAF
School of Aerospace Medicine, Brooks AFB, Tex. The facility is
composed of two pressure chambers—a laboratory area of 58 m.^{3}, and a
living area of 28 m.^{3}—connected by two air locks (fig. 2). Separate
environmental control systems serve each section and provide accurate
regulation of ambient temperature, water vapor pressure, total
barometric pressure, and gas composition. Wind velocities could be
regulated above baseline values only in the laboratory section, through
utilization of a specially constructed and damped fan bank.

Although subjects spent approximately equal amounts of time
in both the laboratory and the living area during an experiment, all
measurements of insensible water losses by the gravimetric method
were conducted in the laboratory section, where environmental parameters
and subject data were closely monitored. During chamber operation
ambient conditions were monitored by four specially trained personnel,
two for each section, while all subject data as well as chamber-
parameter readouts were supervised by an experiment coordinator.

During measurements of skin insensible water losses, 20 channels of data were collected, displayed, and sampled automatically at 15-second intervals by a digital data aquisition system (VIDAT); all data were stored on digital tape and later tabulated and summarized by computer program. A backup system of analog-tape recording was also utilized, and this system served as the primary system for aquisition of ECG, heart rate, respiratory waveform, and respiratory rates. All data were also recorded manually at 15-minute intervals to provide a further backup and a check of computer accuracy.

The 20 channels of recorded data are listed in table III; also shown are the symbols utilized to denote each parameter and the accuracy of measurement of each channel. All data channels were recalibrated daily. The arrangement of data sensors in relation to the experimental subject is shown in figure 3.

In addition to the 20 parameters directly measured, two temperatures were computed from the telemetry data (table III). These were the average skin temperature (T_s) and the effective wall temperature (T_{ew}), both of which will be discussed herein.

The seven skin temperatures were monitored by disc thermistors fixed in a thin perforated Teflon harness. The harness insured that the thermistors would be placed in the same location with equal amounts of pressure against the skin during each measurement. An average skin temperature was calculated by using the area weighting coefficients of Du Bois and Du Bois (38). Rectal temperatures were

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measured by a Teflon covered thermistor probe, while black-globe and ambient temperature thermistors were placed in a location fixed with respect to the experimental subject. Thermistor probes were repeatedly checked against calibrated water baths.

The effective wall temperature (T_{ew}) was computed by using a number of constants, factors, and parameters, including the black-globe temperature, the ambient temperature, and the subject average skin temperature. T_{ew} reflected the total effective radiative heat load on the experimental subjects (116, 118) and could, therefore, correlate with rates of skin insensible water loss.

$$T_{ew}^* \cong \left[\frac{h(T_{bg}-T_a)+F_{bg}-s}{\epsilon \sigma \ F_{bg-w}} \frac{\left[(T_{bg}+273)^4 - (T_s+273)^4\right]}{F_{bg-w}} + (T_{bg}+273)^4 \right]^{1/4} - 273 \qquad (1)$$

h	Heat transfer coefficient
σ	Boltzmann constant
ϵ	Black-globe emittance
F_{bg-s}	Geometric view factor (globe-subject)
F_{bg-w}	Geometric view factor (globe-surroundings)

Water vapor pressure was measured with a Cambridge thermoelectric dewpoint hygrometer, while total barometric pressure was read by a Wallace and Tiernan bourdon tube apparatus. Gas partial pressures were determined by automatic analyzers (oxygen, by a Beckman F3 paramagnetic analyzer; nitrogen, by a Med-Science Electronics Nitralizer; and carbon dioxide, by a Beckman infrared analyzer). Wind

velocities were measured with an Anemotherm warm-wire anemometer with the velocity probe fixed in relationship to the subjects.

The Electrocardiogram was picked up by two electrodes placed on the chest, and heart rate was derived from the QRS frequency. Respiratory waveforms were reproduced by a sensitive thermistor implanted in the outflow track of the face mask, and respiratory rates were derived by counting the peaks of this waveform.

The rates of skin insensible water loss were determined gravimetrically on a total-body basis through the use of a hydraulic metabolic balance manufactured by the Brookline Instrument Company (as described in Bradhma et al., 18). The original balance was specially adapted for this experiment by several modifications: automatic temperature compensation was introduced; a nonflammable hydraulic fluid (Fluorolubes) was installed; special electronic damping circuits were connected to the scale output; and a steel mesh weighing platform was built. The scale was sensitive to weight changes of $\pm$ 1 gm. with a load in excess of 150,000 gm. The scale output consisted of a variable voltage which was fed both to a Honeywell strip-chart recorder and to computer tape through the VIDAT. A weight change of 40 gm. produced a voltage change of 50 mv., or 1.25 mv./gm. The scale was also calibrated daily with the use of a set of removable 5- and 10-gm. weights. The scale was found to maintain its zero point and its sensitivity without drift. The weight-change records were analyzed to determine the average rate of weight loss (gm./hr.) during each

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experiment. The true rates of skin IWL were calculated by the formula discussed below.

During measurements of weight loss, respiratory water was trapped in a face mask, hose, and Drierite (anhydrous CaSO$_4$) canister system. Environmental chamber air of known temperature and water vapor content was inspired directly into the face mask, and all expired air was passed into well-baffled steel canisters packed with measured amounts of indicator Drierite. Approximately 1,600 gm. of the drying material were placed in each canister before a weight measurement was made on the metabolic scale. The canisters' plus Drierite were weighed to ± 0.1 gm. before each subject run and then fixed to the metabolic scale. After each run the gain in weight of the canister and its hose was measured, and the weight change in grams per hour was computed. Since the canister and hose were fixed to the scale, the water vapor trapped (consisting of both water vapor of the inspired air and water vapor added by the respiratory tract) was continuously subtracted from the overall measurement of insensible weight loss by the metabolic scale.

Theoretical considerations (57) would predict that 1,600 gm. of Drierite could extract all but 0.005 mg./liter of water from an airstream moving at a rate of 550 liters/hr. Such efficiency would mean that all but 0.1% of the total expired water vapor would be trapped in the cylinders if airflow were less than 550 liters/hr. Since each canister was used for a maximum of 40 minutes before the Drierite was

changed, the canisters would absorb a maximum of 15 gm. of water vapor
in that time (assuming 88% saturation). The canisters would be
capable of absorbing 135 gm., however--meaning that they never were
loaded with more than 11% of their maximum absorptive capacity (35, 57).

In actual practice it was found that a color-indicator change
involved less than 25% of canister Drierite at the end of a 40-minute
run. .Repeated measurements of canister efficiency demonstrated that
a minimum of 97% of the expired water vapor was trapped in the
canisters. During all calculations, therefore, it was assumed that
all expired water had been trapped.

Experimental subjects

Seven volunteer subjects were selected from a large group of
basic trainees at Lackland AFB, Tex. The subjects, all male
Caucasians between the ages of 18 and 20, were thoroughly evaluated
as to state of health, and personal and family history; all passed
the Class III Flying physical examination. Pulmonary, hematologic,
renal-electrolyte, and thyroid functions were found to be within
normal limits (table IV). No physical evidence or history of
sweating abnormalities or temperature intolerance could be elicited.
Five of the subjects served throughout the 81-day experimental program,
while subject P.K. was substituted for subject K.F. early in the
project because of a personal problem. Subjects were identified by
letters from "A" to "F" throughout the study with subjects A, B, and C
forming the first experimental group, and subjects D, E, and F forming

the second group. Six subjects were utilized in experiments lasting
24 hours or longer.

Clothing

To provide a maximum surface for free evaporation, all subjects
wore only abbreviated loincloths made of Beta cloth and fastened with
a tie of the same material. Beta cloth was utilized because of its
nonflammability in enriched oxygen environments. The only other
articles of apparel permitted were standard rubber bathroom thongs
which were open across the top and sides. These thongs were always
removed during measurements of weight loss on the metabolic scale.

Project outline

Experiments were conducted over an 81-day period. Table V
illustrates the general plan of insensible weight loss experiments
during this time. An initial control period of 10 days consisted of
three 48-hour experiments at 700 mm. Hg P_B, 14 mm. Hg P_{H_2O}, and low
wind velocities. Ambient temperature was varied from 20° to 28° C.

The experimental period was divided into four parts--the first
lasting 21 days and conducted at 700 mm. Hg P_B. Varying combinations
of P_{H_2O}, T_a, and V were investigated. The second part, also running
21 days, duplicated the experimental conditions of the first, except
for a total pressure of 258 mm. Hg. The third part, running for 13
days, was also conducted at 258 mm. Hg P_B but utilized varying gas
compositions--specifically, 100% oxygen and a mixture of oxygen and
helium--as well as varied P_{H_2O}. The fourth experimental period
spanned 6 days and was run at the intermediate P_B of 480 mm. Hg.

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A final control period of 10 days terminated the project and consisted of repeat experiments at 700 mm. Hg P_B, at varying temperatures and water vapor pressures. A single experiment of 565 mm. Hg P_B and very low P_{H_2O} was also completed to simulate environmental conditions aboard an Air Force medical evacuation aircraft.

A complete listing of the 38 individual experiments, as well as the duration and ambient conditions of each, is given in table VI. Each experiment is identified by a number-letter code; the former denoting the project period and part (table V); and the latter, the specific environmental parameters.

Each experiment varied in duration from 10 to 48 hours. Complete fluid- and weight-balance studies were accomplished only on experiments lasting 24 hours or longer. The shorter experiments involved stepwise changes in water vapor pressure, with all other conditions held constant. During the study subjects were placed on a controlled diet of dehydrated freeze-dried foods of known composition which were rehydrated with measured amounts of fluid just before consumption. The same diet was served throughout the study (table VII) and calculated to keep the subjects at a relatively constant weight (table VIII). Accurate and complete monitoring of all solid and liquid intake could be achieved. During an experiment subjects were allowed free access to water, but all intakes were carefully measured and recorded. All urine and feces outputs were collected for analysis of solid and liquid components.

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Experimental protocol

A period ranging from 24 to 48 hours was provided between experiments to allow the environmental chambers to equilibrate to a new set of conditions and to allow the experimental subjects to recover from any signs or symptoms which might have developed during the previous experiment.

Four hours before each study, subjects were carefully examined by a physician; subjects then examined one another according to a protocol to be described further on. Subjects next underwent 3 full hours of 100% oxygen prebreathing. The oxygen was saturated to between 85% and 95% with water vapor to prevent drying of mucous membranes. Since 180 minutes of oxygen prebreathing would be required to prevent bends development at the higher altitudes studied (i.e., 258 mm.-Hg P_B, or 27,000 ft.), it was decided to institute a uniform prebreathing program for every experiment regardless of P_B. Subjects examined immediately after this prebreathing program showed no new physical signs or symptoms that could be attributed to this experience.

After completion of prebreathing, subjects dressed in Beta cloth loincloths and thongs. Half of the experimental subjects (A, B, and C) then entered the laboratory section of the environmental complex through the airlock. Total-body weights were obtained for each subject on the metabolic scale.

A typical plan of a 24-hour experiment is shown in figure 4. After an hour of equilibration within the chamber, each of the subjects

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underwent the first measurement of insensible water loss rates on

the metabolic scale. The subject was connected to the Teflon harness,

to all sensors, and to the mask-Drierite system. After a few minutes

of equilibration during which time the scale was zeroed, an actual

weight measurement period of precisely 30 minutes was initiated.

During this 30-minute period all 20 channels of data were recorded

both manually and on computer tape. At the precise termination of the

period, all data aquisition was ended and the Drierite canister dis-

connected and reweighed.

After the first group of subjects had completed the initial

measurements of IWL rates, they moved into the living area of the

environmental complex, where they ate and then slept. The second

group of subjects (D, E, and F) then entered the laboratory section,

where total body weights and rates of IWL were determined. During the

remainder of the experiment, the two groups of subjects exchanged places

several times; while one group underwent weight measurements in the

laboratory, the other ate or slept in the living area.

Throughout the study, each subject evaluated himself for

symptoms of discomfort at fixed intervals and also evaluated other

subjects for sign development. All subjects were allowed only mild

activity and were provided with television, radio, checkers, chess,

and limited reading material. Approximately 35% of the total

experiment time was provided for sleep, and subjects were given

three meals in a 24-hour period. During the 48-hour experiments

each of the 6 subjects underwent IWL rate measurement four times; and during the 24-hour experiments, three times. During the shorter 10-hour studies, only 3 subjects were used, and each underwent two IWL determinations. At the conclusion of each experiment every subject again underwent a total-body-weight determination, and the net gain or loss of weight during the study was calculated.

Measurement of skin IWL (W_{e_1})

The rate of skin insensible water loss was calculated utilizing the rate of weight loss per hour as measured on the metabolic scale. This observed rate of weight loss did not provide a true measure of skin IWL, however, for two reasons. First, the Drierite canister which is fixed to the scale collects not only water added to the expired air by the respiratory tract but·also water vapor contained in the inspired air. The weight of this amount of inspired water vapor can be easily estimated, however, if the precise ambient conditions are known and the pulmonary ventilation of each subject under those particular ambient conditions has been measured (table IX). Expired gas volumes were measured with a Tissot spirometer, corrected to ambient parameters, and then used to closely estimate pulmonary ventilation and the amount of water added to the canisters by the inspired air.

The second factor which must be considered relates to the insensible weight loss due to metabolic gas exchange: i.e., that weight of CO_2 expired which exceeds the weight of O_2 absorbed. This weight loss (IWL_G) forms part of the weight loss measured by the metabolic

scale and, thus, must be corrected for. Rates of gas exchange

were determined for all subjects while on the experimental diet and at

complete rest (table X). Oxygen and carbon dioxide content of expired

air were measured with a Beckman F_3 paramagnetic analyzer and a Beckman

infrared analyzer, respectively. Respiratory quotients and

W_{O_2} - W_{CO_2} values were measured from 20° to 28° C. T_a, and these

values were utilized in determining the rates of true skin IWL (W_{e_1})

with the following formula:

$$W_{e_1} = W_{ms} + W_{ig} - W_G \tag{2}$$

where:

W_{e_1} is the direct measurement of skin insensible water loss (gm./hr);

W_{ms} is the weight change on the metabolic scale (gm./hr);

W_{ig} is the weight of water vapor in the inspired gas (gm./hr.); and

W_G is the IWL due to metabolic gas exchange (gm./hr.).

Values for W_{e_1} were finally divided by the BSA measurements of each

experimental subject (table IV), so that all IWL_S rates could be

expressed as grams per square meter per hour. Since skin insensible

water loss rates clearly depend upon skin surface areas, the expression

of W_{e_1} in grams per square meter per hour makes the data from differing

environmental situations more directly comparable and negates major

differences in subject size. Values of $W_{e_{1_t}}$ in terms of total grams per

experiment were also computed by use of the formula:

$$W_{e_{1_t}} = W_{e_1} \times BSA \times Duration \qquad\qquad (3)$$

where:

$W_{e_{1_t}}$ is the total average skin IWL per experiment (gm.);

W_{e_1} is the average skin IWL (in gm./m.^{2}/hr.);

BSA   is the body surface area of the subject (m.^{2}); and

Duration   is the length of the experiment (hr.).

Measurement of respiratory water loss (W_R)

Water in the expired air was trapped in the Drierite-canister system and weighed to $\pm$ 0.1 gm. after each determination of skin IWL. This weight change, however, also represented the weight of water carried in the inspired air, as well as water added by the respiratory system. To obtain the true rate of respiratory insensible water loss (IWL_R), the weight of the water in the inspired air must be subtracted from the total canister weight change. This weight of inspired air water (W_{ig}) was discussed previously in the measurement of skin IWL. The determination of IWL_R, or W_R, then becomes:

$$W_R = W_{dr} - W_{ig} \qquad\qquad (4)$$

where:

W_R is the respiratory insensible weight loss (gm./hr.);

W_{dr} is the weight change of Drierite canister (gm./hr.); and

W_{ig} is the weight of water vapor in the inspired air (gm./hr.).

Values for W_R were also expressed in grams per square meter per hour so that major differences in subject size could be negated. A W_{R_t} value

in terms of total grams per experiment was computed in the same manner as the $W_{e_{1_t}}$ value discussed above.

Measurement of total insensible water loss (IWL_T)

The total IWL is composed of skin insensible water loss (IWL_S), as measured by W_{e_1}; of respiratory insensible water loss (IWL_R), as measured by W_R; and of metabolic insensible weight loss (IWL_G), as measured by $W_{O_2} - W_{CO_2}$.

Therefore:

$$IWL_T = W_{e_1} + W_R + W_G \tag{5}$$

Values for IWL_T were finally expressed in grams per square meter per hour, as were W_{e_1} and W_R—to negate major differences in subject size. An IWL_T value in terms of total grams per 24 hours was also derived so that total amounts of insensible water loss per day could be compared under varying environmental conditions.

Fluid balance studies

In all experiments of 24- and 48-hour duration, careful weight- and fluid-balance studies were conducted. All intakes and outputs were measured and tabulated for each subject. In addition, precise initial and final weighings ($\pm$ 1 gm.) on the metabolic scale were carried out. From these data an indirect calculation of skin insensible water loss (W_{e_2}) was derived by use of the complete weight balance formulas shown in table IC. In the final analysis:

$$W_{e_2} = W_A - W_Z + W_I - W_O + (W_{O_2} - W_{CO_2}) \tag{6}$$

In this case, $W_{O_2} - W_{CO_2}$ is not comparable to the W_G values

discussed above, since average metabolic activity during the entire

experiment is considerably higher than the basal activity measured

when the subject is lying on the metabolic scale. Table XI shows

the values for $W_{O_2} - W_{CO_2}$ based on an average estimated oxygen

consumption of 25 liters/hr. as compared with a basal level of

16 liters/hr. These values were used in calculating W_{e_2} by the above

formula. The values obtained for W_{e_2} (gm./experiment) were then

expressed as $W_{e_{2_t}}$ (gm./24 hr) and compared with the values obtained for

$W_{e_{1_t}}$ (gm./24 hr.). Other fluid balance terms are defined in table IIC.

In all studies, data from participating subjects were averaged to give

a single mean value per experiment.

Sign and symptom evaluations

Throughout all studies, but with special emphasis on the 24- and

48-hour experiments, evaluation of signs and symptoms related to

environmental conditions was carried out. These evaluations consisted

of several parts.

Before subjects entered the chambers to commence an experiment,

they received a physical examination by a physician. This examination

was repeated when subjects left the chambers at the conclusion of an

experiment. The physician filled out an Objective Evaluation Sheet

on each subject at these times (table XII). In addition to evaluating

the eight anatomical areas listed on the sheet, he was required to

provide an overall impression of the well-being of the subject and to

list other abnormal signs that he might find. He also administered several sensory tests including a Schirmer test, near and distant visual acuity test, olfactometry, and gustometry. These tests will subsequently be discussed in detail.

All of the experimental subjects were trained to evaluate their own symptoms and to detect and evaluate signs in other subjects. Before the studies began they were given a course of instruction by the Ophthalmology and Otolaryngology Departments of the USAF School of Aerospace Medicine. In this course they were familiarized with the signs and symptoms which might develop under adverse ambient conditions and were given practice in evaluating and grading them by use of subjective and objective evaluation sheets which were provided (table XII). Subjects were also instructed on the technics of performing Schirmer's test and visual acuity tests within the chambers.

Before each experiment, a subject would evaluate himself by the Subjective Evaluation Sheet and would then evaluate a specific partner with the Objective Evaluation Sheet. Upon entering the chamber and at specific intervals throughout the study, these subjective and objective evaluations would be carried out. The subjects made final evaluations immediately upon leaving the chamber.

During the first 8 hours of an experiment, subjective evaluations were conducted hourly and objective evaluations every 2 hours. After 8 hours, subjective evaluations were conducted at 2-hour intervals and

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objective evaluations at 4-hour intervals (except when subjects were
sleeping). Evaluations were usually programmed to occur both immediately
before and immediately after a sleep period. Visual acuity and Schirmer
tests were conducted at 8-hour intervals.

A subjective frequency-severity index was derived to describe
sign development quantitatively, and an objective frequency-severity
index derived to describe symptom development. These indices depended
upon the difference in magnitude between a sign or symptom level
originally reported in an anatomical category (i.e., "Eyes") and the
highest level subsequently reported in that category. If a subject
initially noted a "1" in a category, but later reported a "3", the
difference was then tabulated as "-2". For each anatomical category
the changes or differences were averaged for the subjects involved.
The anatomical averages were then added together and divided by the
number of anatomical categories (always 10) to give an overall average.
This average represented the sign or symptom index value.

$$\text{Index number} \quad \frac{\sum\limits_{n=1}^{10}\left[\dfrac{\sum\limits_{i=1}^{n_s}(x_{i_o} - x_{i_m})}{n_s}\right]_n}{10} \quad (7)$$

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where:

x_{i_o} = Initial value

x_{i_m} = Maximally changed value

n_s = Number of subjects

n = Anatomical categories (1-10)

i = Subjects (1 → n_s)

For each experiment three initial indices were derived: a physician objective evaluation, a subject objective evaluation, and a subject subjective evaluation. The first two of these were averaged to provide an overall Sign Frequency-Severity Index, while the third stood alone as the Symptom Frequency-Severity Index. The three averaged together formed the Sign-Symptom Index.

The relative frequency and severity of signs and symptoms by anatomical region were derived by looking only at the regional averages:

$$\left[\frac{\sum_{i=1}^{n_s} (x_{i_o} - x_{i_m})}{n_s} \right] \tag{8}$$

The time course of sign and symptom development was derived by measuring the change in sign or symptom severity with respect to time

rather than looking at the maximum change. The formula then became:

$$\sum_{n=1}^{10} \left[\frac{\sum_{i=1}^{n_s} (x_{i_o} - x_{i_t})}{n_s} \right]_n \over 10 \tag{9}$$

where:

x_{i_o} = Initial sign or symptom value

x_{i_t} = Value at specific point in time (1 to 48 hours)

Since in all the indices the maximum or time-dependent value was subtracted from the initial value, the sign or symptom index would have a value of "zero"-if there were no change in any subject in any anatomical area during an experiment. As signs or symptoms became more severe, the indices would become increasingly negative in value, and if signs or symptoms actually improved during an experiment, the indices would have a positive value.

Other sensory tests

1. Schirmer's test. Small strips of filter paper (No. 42) measuring 30 mm. by 5 mm. are folded to form a 4-mm. hook on one end. This hook is then carefully placed over the lower eyelid so that it is in contact with the palpebral conjunctivum, and the eye is closed. After 120 seconds, the strip is removed from the eye and a measurement is made of the amount of the strip that has become wet; i.e., somewhere between 0 and 30 mm. Although the presence of the

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strip against the conjunctivum initially acted as a foreign body to induce excessive tearing, it was found that subjects quickly accommodated to the procedure. After several weeks of practice, the strips could be readily introduced without any initial tearing. This test was performed before chamber entry and again immediately upon exiting. The difference in wet length between the initial and final measurement ($L_i - L_f$) was used as the increment of Schirmer change.

2. Visual Acuity. Both near and distant visual acuity were tested at varying times before, during, and immediately after an experiment. Standard 20-ft. acuity charts for distant vision and reading cards for close acuity were utilized. Any alteration in the smallest type that could be read was noted as a change in acuity, with a value of -1 given for each line of larger type and a value of $+1$ for each line of smaller type that the subject was forced to accept as threshold.

3. Gustometry. Taste acuity was measured by a device developed by the Otolaryngology Branch of the USAF School of Aerospace Medicine. This apparatus is based on the principle that taste receptors can be activated by small electric voltages passed across the tongue. The threshold of voltage stimulation of the taste receptors bears a close relationship to the sensitivity of the receptors, and any damage to them greatly increases the voltage threshold. The instrument, itself, consists of two small conducting paddles which are placed on either side of the tongue. A gradually increasing voltage is passed across the tongue until the subject notes a strong metallic taste.

This voltage value was taken as threshold. Threshold values ranged from 100 to 500 mv. Changes in threshold were denoted by $(v_i - v_f)$, where v_i was the initial voltage value and v_f was the value at the conclusion of a study.

- 4. Olfactometry. Olfactory acuity was also measured by a device developed by the USAF School of Aerospace Medicine, Otolaryngology Branch. Four varieties of odor—cinnamon, mint, clove, and cologne—were serially diluted by a factor of 2X in bottles numbered from 1 to 10, the former being the strongest and the latter the weakest odor. Subjects were asked to begin with the weakest bottle (No. 10) and to sniff bottles of increasing concentration until they could clearly identify the odor. Any change in olfactory threshold in this test given immediately before, and then immediately following, an experiment was noted for each of the four odors. These differences were then summed:

$$\text{Olfactory index} = \sum_{n=1}^{4} (S_i - S_f)$$
(10)

where:

S_i is the initial odor threshold;

S_f is the final odor threshold; and

$1 \rightarrow 4$ are the four odors tested.

Decreases in olfactory sensitivity, therefore, led to a positive value for the olfactory index, while increases in sensitivity led to a negative index value.

Data handling and statistical treatment

For all of the 24-hour and 48-hour experiments, data from the experimental subjects were averaged, with equal weight being given to each subject (table XIII). Since the rates of insensible water loss, both skin and respiratory, were determined in grams per square meter per hour, major differences in subject size were, for the most part, adequately compensated for. In the 10-hour experiments where two different sets of 3 subjects were utilized alternately, the mean IWL_S and IWL_R values for both sets were similar ($\pm$ 2%), making it possible to compare the data sets directly.

In the wind-velocity experiments, however, subjects H.D. and L.B. were used in one set of measurements and subjects P.K. and W.C. in the second. Considering individual variation this could have resulted in considerable skewing of the data (table XIV).

In an attempt to adjust these two sets of IWL_S data so that they might be comparable with each other and with data derived from the other experiments, corrections for individual subject bias were carried out. These correction values were derived by comparing the IWL_S rate of each subject, averaged for all experiments, with the grand mean IWL_S rate for all 6 subjects in all experiments. The resulting bias values are shown in table XV. When subjects A and B formed a set, this set deviated from the grand mean by only -2.8%. When subjects D and E formed a set, the deviation from the mean was over +9.9%. The IWL_S data were corrected by utilizing a factor of 1.03 for the former set

and a factor of 0.90 for the second set. No bias corrections for IWL_R data were needed since deviations from the grand mean value were not significant.

The effects of each environmental parameter upon rates of IWL_S were initially analyzed by a comparison of differences in paired-sample means. Mean values of IWL_S for each of the subjects were tabulated for a series of experiments in which all environmental parameters except the one being examined were identical. P values were derived by looking at the T-scores of the average paired-sample differences. These values are shown on the figures relating IWL_S to the environmental parameters.

The influence of environmental conditions upon overall fluid balance and the components of total intake and output were analyzed in a similar manner. A comparison of differences of paired-sample means was utilized to derive the P values reported in the water balance figures.

A stepwise multiple regression analysis was also carried out to relate all environmental factors to rates of skin insensible water loss (10). In this analysis, 549 separate determinations of W_{e1} and 20 environmental variables were used to develop a correlation matrix. Multiple correlation coefficients, F values, T values (and corresponding P values) were derived for the significant environmental factors (table XIV).

V. RESULTS

Results will be presented in three sections. The first will involve the relationship of skin insensible water loss (IWL_S) as measured by W_{e_1} to environmental parameters and to other experimental variables such as skin temperature and effective wall temperature. The second will involve the determinations of fluid balance and the various components of fluid loss under changing environmental conditions. In this section data on insensible respiratory water loss (IWL_R), metabolic insensible weight loss (IWL_G), and total insensible water loss (IWL_T) will be tabulated. The third section will contain data on specific sign and symptom development in varying environments and the results of sensory testing in these environments.

Skin insensible water loss (IWL_S)

Results of the direct measurement of IWL_S by the whole-body gravimetric technic are shown in table VI and figures 5 through 12. In all figures "skin insensible water loss" is synonymous with "skin insensible weight loss" since it is, in fact, an actual weight loss that is being determined. Both of these expressions can be denoted by IWL_S.

All of the environmental variables investigated: water vapor pressure (P_{H_2O}), total barometric pressure (P_B), ambient temperature (T_a), wind speed (V), and gas composition (GC)--were found to influence the rates of IWL_S to a very significant degree.

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The specific effects of P_B and P_{H_2O} are seen in figure 5, where rates of skin insensible weight loss are plotted for three total pressures and a variety of water vapor pressures. At all total pressures, the IWL_S is an inverse function of the water vapor pressure at a constant T_a and V. Altering the total pressure does not change the slope of this relationship but shifts the y-intercept. The IWL_S appears to be an inverse function of total barometric pressure, as well. Thus, decreasing the P_{H_2O} from 14 mm. to 4 mm. Hg results in an increase in the rate of IWL_S of over 2.5 gm./m.^{2}/hr. At a P_B of 480 mm. Hg (intermediate between 700 and 258 mm.), the increase in rate is almost 1.2 gm./m.^{2}/hr., or half the above increase. A single experiment performed at 565 mm. Hg P_B demonstrates a slight increase in IWL_S rates commensurate with the relatively small increment of pressure change that was instituted. The P values for the three major barometric pressures tested indicate the statistical significance of these data.

Figure 6 again shows the relationship of IWL_S to P_{H_2O} and P_B. Here, however, the means and standard deviations of the data points are plotted. In figure 7, these same data are again shown, but with the individual data points of the 6 subjects and the total ranges of each experiment. Some subjects, such as subject D, maintained above average rates of water loss while others, such as subject F, consistently maintained lower than average rates. This pattern was consistent throughout the project.

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The effects of varying atmospheric gas compositions, were studied only at 258 mm. Hg P_B (fig. 8). Most studies were run in an atmosphere of 70% O_2 and 30% N_2, which at this pressure provided 180 mm. Hg of O_2. Experiments were then conducted using 100% O_2 and using an oxygen-helium mixture of 70% O_2, 30% He. Although only two levels of P_{H_2O} were investigated with these gas mixtures, some general conclusions may be drawn. The rates of IWL_S in 100% O_2 were higher, but not significantly so, than in the $O_2:N_2$ atmosphere. The rates of IWL_S in the oxygen-helium atmosphere were, however, considerably lower than in either the $O_2:N_2$ or 100% O_2 atmospheres. At both the 6.5- and 9-mm. Hg P_{H_2O} measurements, IWL_S rates in the $O_2:$He environments were more than 20% lower. Not enough points were measured, however, to assure absolute statistical significance.

The effect of ambient temperature on rates of IWL_S is related to the P_B at which measurements are made (fig. 9). At 258 mm. Hg P_B, the effect of T_a was directly related through the range from 20° to 28° C. During this 8-degree rise in T_a, rates of IWL_T increased by more than 3 gm./m.^{2}/hr., or 33%. This direct relationship was noted at all levels of P_{H_2O} studied (4 mm., 8 mm., and 14 mm. Hg). At a P_B of 700 mm. Hg, however, the effect of T_a was still positive but not as directly proportioned. The rate of increase of IWL_S between 24° and 28° C. was much greater than that between 20° and 24° C. T_a. This pattern appeared to hold at all levels of P_{H_2O} studied. P values indicate that the effect of T_a on IWL_S rates was highly significant.

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In figure 10 the mean values and S.D. of data from two diverse environmental situations can be seen.

The interaction of P_{H_2O} with P_B and T_a in determining the rates of IWL_S is shown in figure 11. For any given level of P_{H_2O}, a rise in T_a or a fall in P_B will significantly raise the rate of IWL_S. The effects of temperature and total pressure appear to be uniform over the entire range of P_{H_2O} studied, as the P_B-T_a lines are nearly parallel. An exception is seen in the 700 mm. Hg P_B - 28° C. T_a line. In this situation the rate of IWL_S at 14 mm. Hg P_{H_2O} was much higher than would be predicted—leading to a decrease in the line slope. The high value at 14 mm. Hg P_B can be accounted for by the onset of observable thermal sweating in this high temperature-high humidity situation. This was the only experiment in the entire series where thermal sweating was detected.

The effect of wind speed (V) on the rate of skin insensible weight loss tended to be directly related over the range studied (fig. 12). A striking effect of elevated wind speeds, however, was their tendency to obliterate or cancel the effects of P_B and P_{H_2O}. At wind speeds in the 20 to 40 ft./min. (or 7 to 9 m./min.) range, the effects of varying total pressure and water vapor pressure are apparent. As demonstrated above and shown in figure 12, in the region of low wind speed or free convective cooling, lowering P_B or P_{H_2O} leads to significant changes in IWL_S. As the wind speed reaches the region of forced convective cooling (in the range of 100 ft./min., or 30 m./min.), the rate of IWL_S

continues to increase almost linearly. However, the absolute

differences in IWL_S rate related to differences in P_B and P_{H_2O}

continue to diminish as the wind speed rises. Above 200 ft./min. these

differences are no longer significant. Whereas at 40 ft./min. V, the

difference in rate of IWL_S at 258 mm. Hg P_B (as opposed to 700 mm. Hg P_B)

averaged 1.6 gm./m.^{2}/hr., at 300 ft./min. V, this difference was only

0.6 gm./m.^{2}/hr. At 40 ft./min. the rate difference between the two values

of P_{H_2O} (9 mm. and 6.5 mm. Hg) averaged 0.8 gm./m.^{2}/hr., while at 300

ft./min. V, this difference is only 0.1 gm./m.^{2}/hr. Nevertheless,

increasing the wind speed from 40 to 300 ft./min. led to an average

increase in the rate of IWL_S of 3.4 gm./m.^{2}/hr., or 32%.

The individual effects of all environmental variables studied

are summarized in table XIII and in figure 13. Here, the change in rate

of IWL_S produced by each variable is expressed in terms of grams per

square meter per hour per Δ unit environmental change. In the case of

T_a, the unit of environmental change is 1° C.; for P_{H_2O}, it is 1 mm. Hg;

for P_B, it is 100 mm. Hg; and for V, it is 50 ft./min. Whereas increases

in T_a and V cause increases in the rate of IWL_S, increases in P_B and

P_{H_2O} cause decreases in the rate of IWL_S. Although most of the environ-

mental variables show almost linear effects over the ranges studied, T_a

demonstrates a varying effect in its high and low ranges.

The possible role of average skin temperature as a determinant

of the rates of skin IWL was also investigated. It became apparent

in experiments run at different total pressures, but otherwise

identical ambient conditions, that skin temperatures always were higher at lower barometric pressures. For a given T_a, skin temperatures were as much as 0.8° C. higher at 258 mm. Hg P_B than at 700 mm. Hg P_B (figure 14). This skin temperature difference was noted only with low wind speed and was abolished by V higher than 100 ft./min.

In figure 15 a large number of IWL_S rates measured at varying environmental conditions are plotted against skin temperature. Several features are apparent. Most prominent—although a wide scatter is present—is the apparent direct correlation between skin temperature and rates of IWL_S. Because of the wide scatter, however, it is unlikely that skin temperature is the only variable involved in the determination of IWL_S rates. A second important feature is the profound effect of elevated wind velocities in increasing the rates of IWL_S for a given skin temperature. At V greater than 100 ft./min., higher rates of IWL_S were noted at lower skin temperatures than were encountered in quieter air. A final feature to be noted is the lack of clear differentiation between the data points of 258 mm. Hg and those of 700 mm. Hg P_B. This feature would suggest that the effect of P_B on rates of IWL_S is partially mediated by changes in skin temperature.

Another possible determinant of skin insensible water loss rates that was investigated was effective wall temperature (T_{ew}). As discussed above, T_{ew} was thought to reflect the total effective radiative heat load on the subjects while they were lying on the metabolic scale.

This parameter was consistently higher than ambient temperature (table VI), with the most striking elevations noted with reduced P_B and with elevated V. In the stepwise multiple regression analysis (table XIV), T_{ew} was found to have the greatest correlation with IWL_S of any single environmental measurement. A correlation coefficient of .530 and a P value of less than .001 were noted.

In addition to T_{ew}, high correlations were noted with P_{H_2O}, T_a, V, and P_B. The average molecular weight of the atmospheric gases also exhibited a surprisingly high correlation with IWL_S, having a P of .001. When a multiple correlation coefficient including all six of the important environmental measurements was derived, a value of .684 resulted.

In all of the experiments in which rates of IWL_S were measured, a mean value expressed in grams per square meter per hour was derived from the individual subject values. As noted above, some subjects consistently ran close to the average, while others ran above or below the average with the same consistency. In table XV the overall deviations from the grand mean IWL_S value in a large number of experiments are shown for each of the 7 experimental subjects. Five of the subjects deviated less than $\pm$ 6% from the grand mean in their own mean values, while the remaining 2 deviated by close to $\pm$ 15%. In all experiments, subject P.K. tended to produce the highest value in the range, while subject M.K. produced the lowest value.

Intra-subject variations—i.e., variations from measurement to measurement in a single subject—in IWL_S rates occurred in all experiments. In the 48-hour studies where four separate determinations of skin water loss were made, differences of up to 2 gm./m.^{2}/hr. were observed in a single subject under fixed environmental conditions. An analysis of replicate runs, however, failed to show any significant time trends or any relationship to time spent in the environmental chamber.

The means, standard deviations, and standard errors for the four sets of replicate runs by the 6 subjects are shown in table XVI for two typical experiments. In these 12 sets of replicate runs (4 runs per set), the S.D. ranged from .32 to 1.52, and the S.E. from .16 to .75. All values are expressed in grams per square meter per hour.

Fluid balance studies

Complete intake and output studies were done on all subjects in experiments lasting 24 hours or longer (27 experiments). Data collected or computed included total intake (W_I), total output (W_O), change in body weight (ΔW), total respiratory water loss (W_{R_t}), total direct skin insensible weight loss ($W_{e_{1_t}}$), total indirect skin insensible weight loss ($W_{e_{2_t}}$), grand total output ($W_O + W_{e_{1_t}}$), and total insensible weight loss (IWL_T). Mean values for each of the 27 experiments are shown in table VI, along with partial data from the 11 shorter studies.

To ascertain whether fluid balance was maintained in a relatively

steady state at the start of the project, total intake and grand total

output were compared during the initial 7 experiments which occupied

the first 20 project days (fig. 16). During these experiments, total

intake was relatively constant averaging 2,380 gm., while grand total

output averaged 2,070 gm. No 24-hour intake varied more than 120 gm.

from the mean, and no 24-hour output more than 150 gm. The discrepancy

between total intake and grand total output was expected and will be

discussed.

That the experimental subjects maintained a relatively constant

overall weight balance throughout the 12-week study can be seen in

table VIII. In 4 of the 7 subjects, the maximum weight change

(initial minus final) during the entire experiment was less than

450 gm. In a fifth, the change barely exceeded 1,000 gm. In subject E,

however, a steady increase in weight occurred, resulting in a net weight

gain of 3,116 gm. during the experimental period. No ready explanation

for this unusual gain could be offered except that this subject was con-

sistently receiving a larger caloric intake than his overall activity

level could utilize.

The individual effects of 4 of the 5 environmental parameters

discussed above upon the maintenance of fluid balance were investigated.

The effect of P_B upon fluid balance and the routes of insensible water

loss was determined by pairing all experiments which were alike in

physical parameters other than P_B (fig. 17). Total intake in the

258 mm. Hg P_B experiments averaged 140 gm./24 hr. more than in the 700 mm. Hg experiments. This difference was significant to the .05 level. The difference in grand total output was even more striking and in the opposite direction, with the 258 mm. Hg P_B experiments averaging 260 gm. less than the 700 mm. Hg. This was significant to the .01 level. Differences in respiratory water loss, skin insensible water loss, and total insensible water loss at the two levels of P_B were also significant at the .05, the .01, and the .1 levels, respectively. No significant differences in weight change could be detected, although subjects tended to lose weight at 700 mm. Hg P_B and gain weight at 258 mm. Hg P_B.

The effect of changes in P_{H_2O} on fluid balance is seen in figure 18. Here, differences in W_I at the three values of P_{H_2O} are not statistically significant, while differences in grand total output are significant to the .05 level. W_R increases significantly ($P < .01$). with decreasing P_{H_2O}, while $W_{e_{1_t}}$ and IWL_T also increase significantly ($P < .01$). Weight changes are again not significant.

Changes in T_a also affect fluid balance (fig. 19). With higher ambient temperatures, there is a significant increase in W_I, coupled with a barely significant decrease in W_0. At 28° C. W_I averaged 260 gm. higher than at 20° C., while W_0 averaged 210 gm. lower. Significant increases in W_R, $W_{e_{1_t}}$, and IWL_T, with increasing ambient temperature, were also noted. Again, weight changes were not statistically significant, although a tendency to gain weight at higher temperatures was noted.

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Finally, the effect of varying gas composition at 258 mm. Hg P_B was examined (fig. 20). In paired experiments it was noted that the only statistically significant weight differences in the three atmospheres involved W_{e1_t} (P <.05) and IWL_T (P <.05), when N_2 was replaced by He.

By use of the total weight balance equations discussed above, an indirect calculation of skin insensible weight loss was accomplished (W_{e2_t}) in the 27 experiments, where complete intake and output measurements were done. The values of W_{e2_t} are given in table VI, together with a comparison of values of W_{e1_t} and the difference between these two values for skin IWL. In almost all cases the value of W_{e2_t} is higher than that of W_{e1_t}. In 27 of 28 experiments, however, this difference is less than 400 gm./24 hr., and in 21 of 28 experiments it is less than 250 gm./24 hr.

Direct and indirect calculations of $IWL_S/24$ hr. at varying P_{H_2O} and T_a are shown in figures 21 and 22. It is again apparent that the indirect calculation (W_{e2_t}) produces a higher loss value than the direct measurement (W_{e1_t}). At higher wind speeds, values for W_{e1_t} are greater than at low speeds, but the effects of P_B and P_{H_2O} are again muted.

Insensible respiratory loss rates (W_R) for all experiments are given in table VI and are expressed as both grams per square meter per hour and total grams. The relationship of W_R to P_{H_2O} is seen in figure 23, where values for 700 mm. Hg P_B and 258 mm. Hg P_B are

plotted separately. Rates of insensible respiratory water loss increase

rapidly and nonlinearly with a decrease in P_{H_2O}. At a reduced P_B this

increase is less rapid; at 258 mm. Hg P_B, W_R increases by only

3.0 gm./m.^{2}/hr. from 14 to 4 mm. Hg P_{H_2O}, while at 700 mm. Hg P_B,

W_R increases 3.9 gm./m:^{2}/hr. over the same range of P_{H_2O}. At

14 mm. Hg P_{H_2O} the difference in W_R, comparing 700 mm. Hg P_B with

258 mm. Hg P_B, is only 9%; while at 4 mm. Hg P_{H_2O} this difference has

increased slightly to 13%.

Rates of IWL_R also increase rapidly and nonlinearly with

increases in T_a (fig. 24). At 258 mm. Hg P_B this increase is less

rapid than at 700 mm. Hg. Increasing the ambient temperature from 20°

to 28° C. results in an increase in W_R of 2.3 gm./m.^{2}/hr. at 258 mm. Hg P_B,

and an increase of 2.9 gm./m.^{2}/hr. at 700 mm. Hg. At 20° C. T_a the

difference in W_R comparing 700 mm. Hg P_B with 258 mm. Hg P_B is 8%,

while at 28° C. this difference is 11%.

If the rates of W_R are plotted only against the relative

humidity (R.H.) of the inspired air, an interesting relationship

can be seen regardless of T_a or P_{H_2O} (fig. 25); W_R appears to be

related only to R.H. and to P_B, with all data points falling on the

two P_B lines despite variations in ambient temperature. Again the

relationship to R.H. is nonlinear, with a more rapid increase in

W_R at the higher total pressure (700 mm. Hg) than at the lower

(258 mm. Hg). The average pulmonary ventilation rates in liters per

hour are shown, and the ventilation at 258 mm. Hg P_B is 10% lower than

at 700 mm. Hg. This 10% difference in ventilation rates could account for almost all of the observed differences in W_R at the two total pressures.

If the rates of skin insensible water loss (W_{e_1}) are plotted in a similar manner against R.H. (fig. 26), a relationship to R.H. and P_B also exists, but the values are also strongly influenced by changes in ambient temperature. This indicates an effect of T_a upon IWL_S which is independent of the effect of T_a upon ambient relative humidity.

Total insensible weight loss measurements (IWL_T) were computed for all 38 experiments in both grams per square meter per hour and in grams per 24 hour (table VI). Values ranged from lows of 10.4 gm./m.^{2}/hr. and 496.8 gm./24 hr. to highs of 22.6 gm./m.^{2}/hr. and 1,065.2 gm./24 hr. In all P_{H_2O} conditions values of IWL_T were greater at 258 mm. Hg P_B than at 700 mm. Hg P_B (fig. 27). This difference tended to diminish, however, as P_{H_2O} decreased, largely because of the increasing contribution of IWL_R at the lower water vapor levels. At 4 mm. Hg P_{H_2O}, in fact, IWL_R actually exceeded IWL_S at 700 mm. Hg P_B. In all other cases, IWL_S was substantially larger than IWL_R, and the contribution of IWL_G was minor and relatively constant.

The effect of T_a on the components of IWL_T is seen in figure 28. At 20° and 24° C. T_a, IWL_T is considerably greater for 258 mm. Hg P_B than for 700 mm. Hg P_B. At 28° T_a, however, IWL_T is actually slightly greater for 700 mm. Hg P_B than for 258 mm. Hg P_B. This reversal is

caused by the increasing difference in IWL_R with rising temperature at the two pressures, coupled with an increased rate of IWL_S with rising temperature at 700 mm. Hg. IWL_G diminishes very slightly as T_a rises. As expected, maximum values for IWL_T are seen at 28° C. and minimum values at 20° C. T_a regardless of total pressure.

Surveying all 38 experiments, it can be seen that the contribution of IWL_S, IWL_R, and IWL_G to total insensible weight loss (IWL_T) shows considerable variation (examples are shown in fig. 29). In a low P_B, high P_{H_2O}, and low T_a experiment, skin insensible weight loss comprised 60.9% of the IWL_T, with respiratory insensible loss contributing only 25.5% and IWL_G 13.6%. In a high P_B, low P_{H_2O}, intermediate T_a experiment, IWL_S comprised only 48.5% of IWL_T, while IWL_R contributed an almost equal 43.9%. IWL_G contributed only 7.6% of the total. In an intermediate environmental situation, IWL_S contributed 53.4%, IWL_R 39.3%, and IWL_G 7.3% to the IWL_T.

Sign and symptom development

Sign and symptom frequency-severity index values for experiments lasting 24 hours or longer are summarized in table XVII. In all cases the Symptom Index (subjective evaluation by subjects) was the more sensitive indicator of a response to the environment. The mean Symptom Index value for all experiments was −.79, as compared to a −.44 for the Subject Sign Index and a −.24 for the Physician Sign Index. Both Sign- and Symptom-Index values became more negative as P_{H_2O} diminished, with the Sign-Symptom Index falling from −0.36 to −0.74 when P_{H_2O} was varied from 14 mm. to 4.5 mm. Hg.

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Sign and symptom development as related to P_B and P_{H_2O} in all

experiments of 24 hours or longer duration is shown in figure 30.

"Symptoms Only" values are derived from the Symptom Index, while

"Signs and Symptoms" values are derived from the Sign-Symptom Index.

Both signs and symptoms were more severe at 258 mm. Hg P_B than at

700 mm. Hg P_B at almost all levels of P_{H_2O}. At 700 mm. Hg P_B a sharp

increase in both signs and symptoms began only after P_{H_2O} had been

reduced below 6.5 mm. Hg. At 258 mm. Hg P_B, on the other hand, a sharp

increase in signs and symptoms began when P_{H_2O} had fallen below 9 mm. Hg.

At 4 mm. Hg P_B, signs and symptoms increased rapidly regardless of total

pressure.

When only the 48-hour experiments are examined, similar results

can be seen (fig. 31). Whereas the symptom index remains relatively

constant as P_{H_2O} is reduced from 14 mm. Hg to 6.5 mm. Hg at a P_B of

700 mm. Hg, a steep rise in the index occurs at 9 mm. Hg P_{H_2O} when P_B

is reduced to 258 mm. Hg.

The effect of ambient temperature upon the development of signs

and symptoms is also significant (fig. 32). Between 24° and 28° C.

there is relatively little change in signs or symptoms. As the T_a

falls to 20° C., however, a dramatic increase in symptom severity occurs

with 700 mm. Hg P_B; this increase is not seen with 258 mm. Hg P_B.

A similar but less important change also occurs in the sign-symptom index.

Subjects appeared to be more adversely affected by the colder T_a at

normal pressures (700 mm. Hg) than at lower total pressures (258 mm. Hg).

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The timecourse of symptom and sign development was examined only in the 48-hour experiments. Symptom development over a 48-hour period at four levels of P_{H_2O} and two levels of P_B are shown in figures 33 and 34, respectively. At 14 mm. Hg P_{H_2O} a very gradual and slight decrease in the symptom index occurred during the first 18 hours, leveling off thereafter. A minimum value of -0.6 was noted at 258 mm. Hg, and a value of -0.54 at 700 mm. Hg P_B.

At 4 to 5 mm. Hg P_{H_2O} changes were more rapid and severe. During the first 18 to 20 hours, index values rose steeply with the sharpest changes in the first 6 hours. After the first 20 hours, index values remained relatively constant with a minimal value of -1.2 attained at 700 mm. Hg, and a value of -1.3 reached at 258 mm. Hg P_B.

As expected the time course of symptom changes at 6.5 mm. and 9 mm. Hg P_{H_2O} fell between that for 4.5 mm. and 14 mm. Hg P_{H_2O}. An increase in symptoms was again noted over the first 20 hours followed by a leveling off. At any point in time, symptoms were usually more severe at 258 mm. Hg than at 700 mm. Hg P_B. At 9 mm. Hg P_{H_2O}, the effect of P_B on the rate and severity of symptom development was particularly evident, with a 32% index difference between 700 mm. and 258 mm. Hg after 12 hours.

Sign development over a 48-hour period at four levels of P_{H_2O} and two levels of P_B is shown in figures 35 and 36, respectively.

Changes here paralleled those noted in symptom development. At 14 mm.

Hg P_{H_2O} a slight change in sign severity occurred over the first

10 hours. At 4 to 5 mm. Hg P_{H_2O} a rapid change in the index took place

during the first 18 hours with the steepest change in the first 6 hours.

A minimum value of -1.0 was reached for 700 mm. Hg, and a value of

-1.1 for 258 mm. Hg P_B. After the first 20 hours few changes were noted.

With a P_{H_2O} of 9 mm. Hg a striking difference in sign development

related to P_B was seen. In the 258 mm. Hg experiment, a low index

value was present from the very start and changed only slightly

through the entire run. This initial low value was produced by the

fact that 2 of the experimental subjects had developed viral sore

throats before the start of the experiment and presented signs of

throat irritation well out of proportion to their symptoms. Very

little progression of these signs was noted during the 48 hours of

the experiment, however. At all levels of P_{H_2O}, sign development

was generally more rapid and more severe at 258 mm. Hg P_B than at

700 mm. Hg.

The effects of P_B, P_{H_2O}, T_a, and GC on the frequency and

severity of sign and symptom development in each of the anatomical

areas or categories evaluated for the indices are shown in figures 37

through 46. In a summary of all experiments, 24 hours or longer

(fig. 37), the "Nose" category was the most frequently and severely

involved in respect to symptoms. In decreasing order, there followed

"Lips," "Pharynx," "Eyes," "Mouth," "Tongue," "Scalp," "Skin," and

General." Nose symptoms were reported with 62% greater frequency or severity than lip symptoms and with 970% greater frequency or severity than general symptoms.

- The effect of barometric pressure (P_B) on area-specific symptoms is seen in figure 38. Except for the pharynx, tongue, and skin, symptoms were more severe in each area at 258 mm. Hg than at 700 mm. Hg P_B. Looking at the mean value, symptoms at 258 mm. Hg averaged 23% greater in frequency-severity than at 700 mm. Hg. The effect of P_{H_2O} on area-specific symptoms (fig. 39) is similar. Except for the pharynx, symptoms were substantially more frequent or severe at the lower value of P_{H_2O} than at the higher. In terms of the mean value, symptoms were 85% greater at 4 mm. Hg than at 14 mm. Hg P_{H_2O}.

When the effect of T_a upon the severity and frequency of symptom development by anatomical region was examined (fig. 40), an unusual pattern emerged. A striking effect of T_a upon nose symptoms was seen, with a greater than 100% increase noted between 28° and 20° C. In all other anatomical regions except the general category, however, this temperature effect was minimal, if visible at all. With lips and pharynx, in fact, the temperature effect was reversed, with greater symptoms occurring at the higher T_a. At 20° C. T_a subjects very frequently complained of increased nasal stuffiness and coryza along with some general discomfort, while other symptoms were not apparent.

The influence of gas composition at 258 mm. Hg P_B on area-specific symptoms was not consistent (fig. 41). Although an increase in symptom severity did occur in 100% O_2 in 6 of the 9 categories, not all of the differences could be called significant. In the O_2:He atmosphere, a decrease in symptoms from the O_2:N_2 mixture was also noted in 6 of the 9 categories. In terms of the mean values, symptoms were 12% more prominent at 100% O_2, and 6% less prominent in O_2:He when compared to the O_2:N_2 atmosphere.

The frequency-severity of signs related to anatomical areas presented quite a different picture. In figure 42, area-specific signs in all experiments 24 hours or longer are shown. The physician evaluation and the subject evaluation are plotted separately and the physician-subject mean value (sign frequency-severity index) is shown. The order of frequency-severity for signs is clearly different from the order of symptoms. Here, the "Lips" category was most prominent followed by "Eyes," "Nose," "Tongue," "Pharynx," "Mouth," "Skin," "Scalp," and General." Whereas, the "Nose" category was most prominent among symptoms, it occupied only 3d place among signs. While "Eyes" held 4th place in symptoms, it moved up to 2d place in signs. As "Lips" moved up from 2d position in symptoms to 1st position in signs, "Pharynx" fell from 3d to 6th. In these experiments lip signs were noted with 33% greater frequency-severity than eye signs, 122% greater frequency-severity than nose signs, and 2,500% greater frequency-severity than general signs.

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The effect of P_B on sign development by area was less striking than its effect on symptom development (fig. 43). A significant increase in severity of signs at 258 mm. Hg as opposed to 700 mm. Hg was noted in lips, eyes, mouth, and scalp. The mean value difference amounted to only 15%, however. In the nose and pharynx area, signs were actually less severe at the lower P_B.

Water vapor pressure produced a more consistent effect (fig. 44). Sign frequency-severity was more notable at 4 mm. Hg P_{H_2O} than at 14 mm. Hg in 8 of the 9 anatomical categories. Only the tongue area failed to show this vapor pressure effect. In the lip area the increase in signs from 14 mm. Hg to 4 mm. Hg P_{H_2O} was over 137%, and the mean value for all areas jumped 117%.

The influence of T_a was found to be minimal (fig. 45). An increase in signs in the lip and eye areas was seen with a rise in T_a, but a decrease in signs was noted in the tongue, pharynx, mouth, skin, and general areas. The mean value difference between 20° and 28° C. T_a was only 15%, with the edge going to 20° C.

The effect of gas composition at 258 mm. Hg P_B on regional sign development is shown in figure 46. In 100% O_2, the frequency-severity of signs was slightly higher in the lip, tongue, mouth, and skin areas when compared with the other gas mixtures. In 70% N_2:30% He, signs were slightly less severe in the lip, nose, tongue, and mouth areas when compared with the other atmospheres. The mean sign values, however showed only a 10% difference in frequency-severity between the 100% O_2 and the O_2:He atmospheres.

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A comparison of anatomical areas in terms of sign and symptom development is shown in table XVIII. The specific symptom or sign that occurred with the greatest frequency in each region is also listed.

The relationship of sign and symptom development to rates of skin insensible water loss and to total insensible water loss is shown in figure 47. A set of environmental parameters which produced a low rate of IWL_S (designated as "A") was used as a baseline for measurements in two environments which produced a high rate of IWL_S (designated as "B" and "C"). All measurements of changes in "B" and "C" are expressed as a percentage change for "A". Whereas, IWL_S increased by 117% and 108% in environments "B" and "C," respectively, IWL_T increased by 94% and 117%. The increase in the sign-symptom indices in these two environments were very similar to the increases in IWL_S and IWL_T, 130% for "B," and 140% for "C." The increase in IWL_R, on the other hand, did not accurately reflect the changes in the sign-symptom indices.

The correlation between rates of skin insensible water loss and the sign-symptom index over the entire range of this experiment is shown in figure 48. Both parameters are expressed as a percent increase over the baseline values. The relationship is curvilinear, with very little change in the sign-symptom index occurring with increases in IWL_S of up to 50% over the baseline. With still higher rates of IWL_S, however, the rate of increase in the sign-symptom index accelerates so that a 120% increase in IWL_S is associated with a 100% increase in the index.

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A summary of the results of the specific sensory tests performed during the 24- and 48-hour experiments is shown in table XIX. Only those changes which have some statistical significance are listed. Visual acuity alterations were found to be minimal in almost all experiments, the exception being the two 48-hour studies run at very low levels of P_{H_2O}. During these two studies subjects reported increased eye irritation in the chambers.

Schirmer's test results were very difficult to interpret, and significant changes were noted in only three experiments with a wide variety of ambient conditions. Tearing appeared to decrease in some atmospheres featuring low P_{H_2O} or high T_a. Gustometry results indicated that some atmospheres tended to diminish taste acuity while others actually increased acuity. The most striking decrease in taste ability occurred with low P_B and low P_{H_2O}. In both experiments utilizing O_2:He atmospheres, taste ability was significantly improved. Changes in olfactory function were also difficult to document, with significant changes occurring in only two experiments. Both of these featured low P_{H_2O} and low P_B, and smell was significantly decreased.

VI. DISCUSSION

Skin insensible water loss:

The measurement of IWL_S by the whole-body gravimetric method has a long history in the scientific literature, (20, 32, 50, 56, 62, 65, 114, 122). Other methods such as the dessicated capsule, diffusion chamber, CaCl bag, electrohygrometry-airflow, gravimetric-airflow, and infrared-airflow systems have fallen in and out of favor (table II). Each of these methods possesses inherent difficulties and errors, and all do not measure identical types of water loss from the skin.

The whole-body gravimetric technic which was selected for this study measures the average rate of weight loss from the entire body. Therefore, not only the so-called diffusional water losses are measured, but all losses - including mental sweating, thermal sweating (if present), metabolic gas exchange, and respiratory water. By utilizing special technics to trap respiratory water and to calculate metabolic gas exchange and by selecting environmental conditions under which thermal sweating will not occur, one is able to measure IWL_S alone (as W_e, which includes W_D and W_M).

All technics which utilize a skin capsule or diffusion chamber to collect water vapor (3, 14, 17, 24, 26, 27, 41, 53, 60, 69, 73, 83, 86, 92, 103, 107, 129)- no matter how the amount of water is actually measured - can look only at rates of skin water loss

from small anatomical areas. Since these areas are usually located on the abdomen, trunk, or forearm (where mental sweating is not present), these technics are actually measuring only W_D, or diffusional water loss. Numerous studies have shown that palmar, plantar, axillary, and head skin are responsible for more than 55% of evaporative heat loss under nonsweating conditions, while making up less than 22% of the body surface area (60, 73). It is these areas which feature significant mental sweating from secretory glands and which give evidence that W_M usually plays a significant role in skin insensible water loss. This role is neglected in the skin capsule technic in which skin areas with prominent mental sweating are not covered.

Utilization of the skin capsule or diffusion chamber technics, also brings some uncertainty as to the accuracy or applicability of the values of IWL_S which are obtained. In the measurement of evaporative rates by these technics, it is impossible to quantitate precisely the ambient conditions at the skin surface under the capsule (92). If a still-air method is uded (dessicated capsule), one cannot easily maintain a fixed temperature or water vapor pressure under the capsule. In order for IWL_S values to be valid, one must assume that the skin will adjust to the new set of conditions in effect when the capsule is fixed to the skin.

When an airflow method is used, the validity of IWL_S readings

is even more suspect. Peiss and Hertzman (92) demonstrated that the collection of water vapor by a moving stream of dry air imposes severe demands upon the skin by dramatically increasing the vapor pressure difference between skin and the air which overlies it. The moving stream of air also induces turbulence at the skin-air interface, and thus creates an "unnatural" environment for water diffusion and evaporation (24). Whether IWL_S rates determined under these conditions accurately reflect normal values is open to considerable question.

A recent study has also demonstrated that measurements of skin water loss rates utilizing the airflow and skin capsule technics are effected not only by the velocity and humidity of the airstream, but also by the size of the capsule and the area of skin that it covers (64). The actual rate of airflow over the skin surface will vary with the shape and size of the subcapsular space overlying the skin, as well as with the measured flow rate of gas into or out of the capsule. As pointed out by Tregear (in Johnson and Shuster, 64) one is always faced with the problem of separating the changes in IWL_S which are related to the skin from those which are related to differences in air movement. In all of these studies the technics used to measure skin water loss significantly change the environment in which the water loss is to be measured.

The examination of previous experimental determinations of skin IWL rates (table II) reveals that values determined by the whole-body gravimetric technic (20, 50, 56, 62, 65, 114, 122) and by the

dessicatéd skin capsule technic (24, 26, 60, 69, 92) are in close agree-

ment, with a mean value for the former set of 10.97 gm./m.^{2}/hr., and

for the latter set of 10.69 gm./m.^{2}/hr. It should be noted that those

values determined by the dessicated capsule method often represent

averages from multiple anatomical sites including palms and soles.

Measurements using other technics show wide variations, with the

electrohygrometry-airflow studies giving a range from 1.5 to 17 gm./

m.^{2}/hr. and the gravimetric-airflow studies, a range from 2.5 to 58.0

gm./m.^{2}/hr.

Rates of IWL_S in this study ranged from 6 to 15 gm./m.^{2}/hr., with

an average value of 9.57 gm./m.^{2}/hr. at 760 mm. Hg P_B and 24° to 28° C.

T_a. These rates compare very closely with those determined by other

investigators who have used the whole-body gravimetric or the dessicated

capsule technics.

Using electrohygrometry and dry airflow, several investigators have

recently shown consistent results in measuring "transepidermal water

loss" from the flexor aspect of the forearm (43, 64, 105). Values of

1.8 to 3.5 gm./m.^{2}/hr. were obtained when experimental technics and

anatomical sites were standardized. These measured rates of transepi-

dermal water loss represent a skin area which shows little or no evidence

of mental sweating or sweat gland activity below the thermal threshold.

It is also an area in which skin resistance to water diffusion is notably

high (92).

It is, therefore, apparent that this skin water loss represents

only W_D, or diffusional water, and that this measurement of W_D is not

representative of the entire skin surface. These factors again make it impossible to draw any conclusions about total-body water losses.

Because of the wide variation in experimental determinations of IWL_S, and because of the questionable effects of environmental conditions, physiologic state of the subject, and technics of measurement, the mechanism of skin insensible water loss is still disputed. The most widely accepted concept - as amplified by Buettner (21, 22, 24) and supported by McCutchan and Taylor (78, 79), Hale et al. (56) Burch and Winsor (26), and others- holds that most skin water loss results from the continuous passive diffusion of water through the epidermis. This water loss takes place through a passive process, and the rate of loss is determined only by the physical characteristics of the epidermis and the environmental conditions of the surrounding air. A simplified equation to describe the water loss is:

$$\text{Water transfer rate per unit area} = -k \ (VP_s - VP_a) \tag{11}$$

where VP_s is the P_{H_2O} at skin temperature, VP_a is the P_{H_2O} at ambient temperature, and K is the permeability constant (6).

In this diffusional water loss (W_D) approach, the skin appendages- i.e., eccrine, apocrine, or holocrine glands - are classically thought to play no role. Support for this concept is derived from experiments on subjects in whom sweat glands are congenitally absent (72, 100, 109) or have been chemically inactivated (14, 27, 95, 119). These subjects all show local rates of skin water loss generally comparable to those of normal subjects - a fact which led Pinson (95) to conclude that

"no part of the insensible perspiration of normal skin is secreted by sweat glands." The holocrine or sebaceous glands have also been eliminated as a contributor to W_D by the small volume of their secretions and the low water content (84).

If a large part of skin insensible perspiration arises by a simple diffusion process, then rates of IWL_S should be largely dependent only upon the vapor pressure gradient between skin and ambient air. Many studies (24, 28, 114) have indeed concluded that this vapor pressure gradient is an important determinant of IWL_S rates, but it has become apparent that other environmental factors such as temperature, air movement, and total barometric pressure also influence the rate of skin water loss.

Taylor and Buettner (113) have restated the effect of the environment upon IWL_S in an "evaporative effect principle": environmental properties which facilitate the evaporation of water from the skin also increase the rate of skin water loss independently of skin temperature or humidity. When evaporative forces are low, as in a high-humidity, low-temperature, high-barometric pressure, and low wind-velocity environment, diffusion of water vapor out of the skin is inhibited by an increase in skin wetness and a repenetration of surface water (96, 97, 111). Support for the evaporative effect has come from the work of Pinson (95), Taylor and Marbarger (112), Hale et al. (56) and McCutchan and Taylor (76, 79). Gagge (44) introduced the equation:

$$E - k_e \, w \, (p_s - p_a) \tag{12}$$

to describe the evaporative loss from a skin surface, where:

E   is the water loss in grams per square meter per hour;

k_e is the vapor conductance between skin surface and
atmosphere;

w   is the wetted proportion of the skin surface;

P_s is the vapor pressure of the skin; and

P_a is the vapor pressure of the atmosphere.

The vapor conductance term (k_e) is dependent upon air movement

and total barometric pressure as well as upon the atmospheric

gas composition.

Further support for a diffusion and evaporation origin of

skin insensible water loss comes from studies of the epithelial

barrier to water vapor in intact and excised normal human skin.

Burch and Winsor (26, 27) demonstrated that excised and clearly

dead human skin retained a normal barrier to water vapor trans-

piration. Other experiments show that the vapor barrier properties

of the stratum corneum are not dependent upon living epidermal

cells, functioning enzyme systems, nor intact cell membranes (16,

73, 83, 89, 107). Several investigators (73, 89) have succeeded

in localizing the water barrier to the inner two-thirds of the

stratum corneum and have characterized it as a hydrophilic lipid-

protein complex. Destruction of this barrier by stripping of

the stratum corneum or the application of lipid solvents results

in a 67-fold increase in water loss with rates of up to 300 gm./

$m.^2/hr.$ (83).

A recent study by Goodman and Wolf (50), however, has presented

data to challenge the passive diffusion-evaporation concept of

skin insensible water loss. Using the skin-capsule and dry airflow

technics, they measured insensible water loss from small areas

of the human skin by means of infrared gas analysis. Because

the relationship between ambient vapor pressure and rate of skin

water loss was found to be nonlinear, these investigators proposed

the alternate hypothesis that only part of IWL_S is caused by water

that has passively diffused through an inert epidermal barrier.

The bulk of IWL_S is due, rather, to the evaporation of water from

eccrine sweat ducts, which are assumed to be filled to the top

with water. They conclude that the observed influence of ambient

vapor pressure on IWL_S is related not to the passive diffusional

component but rather to the eccrine duct component (91).

There is little evidence in the literature to support the

concept that eccrine sweat ducts are filled with water when they

are inactive and thermal stimuli are not present. Indeed, there

is a strong indication that the tubular epithelium of the eccrine

sweat duct unit actively reabsorbs fluid (71, 115). Even at low

rates of active secretion, therefore, reabsorption may exceed

secretion and the ducts may not fill completely. Unless all eccrine

sweat ducts are constantly filled right to the epidermal surface

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with water, evaporation from these ducts is not nearly sufficient

to account for bulk of skin insensible water loss (91).

All of the data presented here (figs. 5 through 13), relating

skin insensible weight loss to environmental variables, are most

compatible with the passive diffusion-evaporation theory of IWL_S.

Contrary to the findings of Goodman and Wolf (50), a nearly linear

and inverse relationship was observed between ambient water vapor

pressure (P_{H_2O}) and IWL_S. Such a relationship had previously

been described by Taylor and Buettner (113), Hale et al. (56),

Thauer et al. (114), and Kerslake et al. (65) up to a P_{H_2O} of 16

mm Hg. Over the measured range from 4 to 14 mm. Hg P_{H_2O}, the change

in rate of IWL_S was consistently -0.27 gm./m.^{2}/hr. for every 1

mm. Hg P_{H_2O} increase.

The conflicting findings of Goodman and Wolf may be related to

several differences in experimental methods. The use of a skin capsule

technic provides data only from small, localized skin areas which

may or may not have mental eccrine activity. The use of an airflow

system of water collection alters the ambient conditions at the

skin-air interface, leading to changes in diffusion and evaporation

rates (92). Also, the most significant deviation from a linear

relationship was noted with P_{H_2O} values greater than 15 mm. Hg - a

region which was not examined in this study.

The documentation of an apparently linear and inverse correlation

between IWL_S and P_B verifies the observations of Hale et al. (56),

and McCutchan and Taylor (79). However, the rate of change of IWL_S of ~0.58 gm./m.^{2}/hr. for every 100 mm. Hg increase in P_B does not approach the theoretical change predicted by Miller (81) of a 3-fold increase in IWL_S when P_B is reduced from 760 to 258 mm. Hg.

An objection may validly be raised that IWL_S rates measured at 700 mm. Hg and those measured at 480 mm. and 258 mm. Hg P_B reflect not only a difference in total pressure but also a difference in atmospheric composition. Although differing ratios of oxygen and nitrogen were utilized at these pressures, it must also be noted that the physical properties of oxygen-nitrogen mixtures are approximately independent of the fraction of each component (30, 117). Such properties as specific heat, thermal conductivity, and viscosity show little variation when the nitrogen content of the atmosphere is reduced from 79% to 30% (table XX). Altering the nitrogen-oxygen ratios should, therefore, have a minimal effect upon the rate of insensible water loss.

The physical properties of an oxygen-helium atmosphere, on the other hand, differ markedly from those of the oxygen-nitrogen mixtures. Thermal conductivity is almost doubled, while heat capacity is reduced by 10% and density reduced by an even greater amount (13, 30). In the comparison of IWL_S rates at 258 mm. Hg P_B, utilizing 100% O_2 and 70:30 ratios of $O_2:N_2$ and $O_2:He$, it is not surprising that rates are very similar in the O_2 and the $O_2:N_2$ atmospheres but significantly different in the $O_2:He$ atmosphere. The 18% lower rate of skin insensible water loss which results when He is substituted for N_2 may be related to the

lower average skin temperatures (fig. 14) and the lower skin temperature
- ambient temperature differences $(T_s - T_a)$ of subjects in the helium
environment. Such temperature differences had been described earlier by
Epperson et al. (40), who also noted a lower rate of evaporative heat
loss at ground level when He was substituted for N_2.

With the greater thermal conductivity of He, one could expect a
more rapid convective heat loss to the atmosphere and a resultant lower-
ing of the skin temperature. The lower rate of evaporative heat loss,
however, would tend to balance out this increased convective loss.

The role of ambient temperature in altering IWL_s must be differenti-
ated from its profound effect on eccrine secretion (25). In order
to measure only W_D and W_M, environmental conditions must be selected in
which W_{T_s} and W_{T_i} do not occur (fig. 1). There is general agreement that
a mean skin temperature at or above 34.2^o C. will lead to thermal sweating
in the resting man (4, 60). Kerslake et al. (65) have shown that, below
an ambient temperature of 28° C., the nude resting subject will not
sweat. Their data also suggest that the rate of skin insensible per-
spiration rises linearly with increases in T_a below the sweating threshold.

Measurements of sweating thresholds on a regional anatomical basis
have, however, indicated that a few areas such as the dorsum of the
foot and the lower calf have a threshold as low as 28° C. T_a and are the
first areas of eccrine activity to be recruited when the ambient temperature
rises (60). One is forced to conclude, therefore, that at ambient tem-
peratures above 26° C., one cannot always exclude the presence of W_{T_i},

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however small it may be.

When one examines the effects of increases in T_a upon IWL_S rates in this study, it is immediately apparent that a consistently positive correlation is present. It is also clear that the _rates_ of change of IWL_S with changes in T_a are not consistent. At 258 mm. Hg P_B the rate of change of IWL_S is + 0.45 gm./m.^{2}/hr. for every 1^O C. increase in T_a over the entire range of T_a and over the entire range of P_{H_2O} (fig. 10). On the other hand, at 700 mm. Hg P_B the rate of increase of IWL_S is only + 0.27 gm./m.^{2}/hr. from 20° to 24° C. T_a, while the rate increases to + 0.72 gm./m.^{2}/hr. from 24° to 28° C. T_a.

Here, one is presented with the first clear instance of an interaction between two environmental variables, T_a and P_B, in their influence upon skin insensible water loss. There is no doubt that the total barometric pressure can exert a direct effect upon the subjective appreciation of ambient temperature, as well as a measurable effect upon such parameters as skin temperature.

Throughout the studies there were far fewer complaints of 20° C. T_a being too cold and 28° C. being too warm at reduced barometric pressures than at ground level. Shivering was never noted at 20° C. T_a at altitude, while it did occur at ground level; sweating was not observed at 28° C. T_a at altitude, but was occasionally detected at ground level. At the same time, average skin temperatures were consistently higher for a given T_a at 258 mm. Hg than at 700 mm. Hg P_B (fig. 14). It is probable that the rarefied atmosphere at 258 mm. Hg resulted in less convective heat loss while fostering an increased evaporative heat

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loss (30, 74, 81). In the ambient temperature range below sweating

threshold, the decrease in convective loss outweighs the increased

evaporative loss, resulting in a skin temperature which is higher

than at ground level. At or above the sweating threshold, enough

skin water is available so that the increased evaporative heat loss

outweighs the reduced convective loss, and the skin temperature should

then fall below that of ground level. This fall in skin temperature

with lower P_B has been observed by Taylor and Buettner (113) and by

McCutchan and Taylor (79) who experimented above 28° C. T_a.

In the current study, the relationship of ambient temperature

to average skin temperature roughly parallels the relationship of

skin temperature to skin insensible water loss (compare figs. 14 and 15).

Even at 700 mm. Hg P_B, however, the relationship between T_a and T_s

is linear, and an increased rate of change of T_s was not noted above

24° C. T_a. Because of these parallels, it is tempting to speculate

that skin temperature is an important mediator of the effects of both

ambient temperature and total pressure upon rates of IWL_S. A discussion

of this possibility will be continued below.

The final environmental factor explored in this study, wind velocity,

also exhibits a complex interaction with other environmental variables

in the determination of rates of skin insensible water loss. At lower

airflows, in the region of predominantly free convective cooling,

this interaction is minimal, and the influence of P_B and P_{H2O} is not

greatly altered. When the wind speed increases sufficiently to cause

significant forced convective cooling, however, the influence of both

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P_B and P_{H_2O} upon IWL_S rates diminishes rapidly.

Unfortunately, most of the determinations of IWL_S in the literature have neglected the effects of V or have studied its effects at ambient temperatures above the sweating threshold (79), or in pressure suits (128). The data of Taylor and Buettner (22, 113) demonstrated a rough correlation between wind speed and total evaporative water loss at any specific skin temperature. As the wind speed increased from 2 to 5 km./hr., water loss rates at a specific skin temperature tended to group together regardless of P_{H_2O}.

Observations, here and in several other studies, indicate that increased air movement tends to lower skin temperature while increasing IWL_S at a given T_a. This lowering of skin temperature (fig. 14) may be directly related to the increased evaporative rate and increased evaporative heat loss. Gagge, however, suggested that surface vasoconstriction may mediate the fall in T_s at higher wind speeds (59).

This alteration in T_s by rapid airflows may be, at least in part, responsible for the diminished influence of changes in P_B and P_{H_2O} upon IWL_S rates under these conditions. The tendency for a low P_B to be associated with an elevated average skin temperature may be counteracted by the higher wind velocities and the resultant increase in forced convective cooling (30). The more rapid air flows over the skin surface may also tend to increase the P_{H_2O} gradient between the skin and air, resulting in an increased rate of evaporation and, perhaps, a concomitant increase in diffusion of water vapor. At high

values of V the air evaporative capacity may increase so greatly that differences in P_{H_2O} assume progressively lower significance to skin water loss rates (92).

In an examination of each of these environmental variables and its effect upon skin IWL, the close correlation of average skin temperature changes with changes in both the environmental variables and IWL_S rates has been noted. Birch and Winsor (27), experimenting with excised human skin in 1944, noted that as the temperature of the skin was increased the rate of water loss increased proportionally. Other studies have confirmed this relationship but have also demonstrated a significant degree of residual variation when IWL_S rates are plotted solely against T_S (3). Taylor and Buettner (113) then pointed out, in 1953, that many other environmental variables could affect skin water loss somewhat independently of skin temperature.

The fact that T_S does not correlate completely with IWL_S rates, however, should not detract from its obviously important involvement in the skin insensible water loss process. The major question remaining unanswered relates to whether the alterations in skin temperature actually cause the changes in IWL_S rates, or whether the physical processes which alter IWL_S rates also alter skin temperature in a parallel manner. Since diffusion and evaporation are involved in skin insensible water loss, it seems likely that T_a would have some direct effect on both of these processes. At the same time, physical changes in the environment, such as increased wind speed, may cause skin temperature to decrease while IWL_S increases. Such changes

provide strong evidence that the relationship of T_a to IWL_S is not

always a consistent one, and that environmental variables may cause

these two measurements to move in opposite directions. Viewing all

of the evidence, one must conclude that T_a does exert some direct

influence on IWL_S rates as do other environmental factors which alter

the rates of diffusion and evaporation. One must also conclude that

these other environmental factors exert a direct effect on T_a, just

as they do upon IWL_S. By changing convective heat losses or evaporative

heat losses, T_a is caused to vary in a direction often parallel to

rates of IWL_S.

The correlation of effective wall temperature (T_{e_W}) with measured

rates of IWL_S has been pointed out in the stepwise multiple regression-

analysis of environmental factors shown in table XIV. Of all the

quantifiable features of the environment studied, T_{e_W} consistently

demonstrated the closest relationship to rates of skin insensible

water loss. Since this term must take into account changes in many

ambient parameters such as black-globe temperature and ambient temperature,

as well as several coefficients which vary with ambient conditions,

it is not surprising that a significant correlation with rates of IWL_S

does appear. T_{e_W} not only gives an indication of the total heat

load on the experimental subject, but also is influenced by the subject's

own surface temperature.

If one compares figure 14, which shows the relationship of average

skin temperature to ambient temperature, with figure 49, which shows

the relationship of average skin temperature to T_{e_W}, a major difference

is seen. For any given ambient temperature, a decrease in P_B is associated with a higher T_s. For any given T_{e_w}, however, a decrease in P_B is correlated with a lower T_s.

The marked increase in heat loss through radiation in the experimental subjects at reduced P_B is reflected in the great increase in T_{e_w} which is also seen. This increase in radiative heat load and in T_{e_w} is sufficient to completely mask the smaller rise in subject skin temperature which also occurs at reduced P_B. Thus, any T_{e_w} at reduced P_B may actually be associated with a lower T_s when compared with a normal P_B.

Although an important influence of five environmental variables upon rates of skin insensible water loss has been demonstrated in this study, the specific physical or physiologic mechanisms which cause the changes in IWL_S rates remain to be defined. The diffusion and evaporation theories of Buettner and Taylor are still the most widely accepted, although they have been challenged, at least in part, by Goodman and Wolf (50) and Peiss and Hertzman (92).

In this discussion, it must be remembered, skin insensible water loss is considered to have two major components when thermal sweating is not activated - W_D and W_M. The former corresponds to the diffusional water loss described by Burch, Buettner, Pinson, and others. Although this water is thought to diffuse directly through the layers of the epidermis, it would not be impossible for a very small percentage to diffuse out of the walls of eccrine sweat ducts and other skin appendages. The latter component (W_M) is composed of water that is

actively secreted by constantly functioning eccrine and apocrine sweat glands that are not under thermal control (61, 99). Like W_D, rates of W_M vary over different skin areas.

Although one can talk theoretically about W_D being the only component of transepidermal insensible water loss and proceed to measure only W_D in an attempt to define its mechanism and controls, this approach will not provide any information about the rates of skin fluid loss from the whole animal as they actually occur. W_M, as well as W_D, must be evaluated on a total-body basis.

Having agreed that IWL_S has two major components, one can logically progress to question whether IWL_S may have two mechanisms of control. The component of water loss provided by W_M represents active glandular secretion, therefore, the process of diffusion will be of lesser importance. The secreted water must be vaporize, however, and be carried away from the body surface; so, the process of evaporation assumes great importance.

The major component of skin water loss provided by W_D will depend upon the processes of both diffusion and evaporation - whether this water diffuses directly through the many layers of the epidermis, or from the sweat ducts (as suggested by Goodman). Regardless of the route through the skin to the surface, the rate of diffusion will depend upon physical parameters in the immediate environment.

Examining the equations which describe the processes of diffusion and evaporation, one can see that all of the environmental parameters

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investigated in this study play an important role.

In the case of diffusion (m):

$$m \cong \frac{Q \left(\dfrac{T_a}{273} \right)^{1.75} \left(\dfrac{760}{P_B} \right) \left(\dfrac{P_{H_2O_s}}{T_s} - \dfrac{P_{H_2O_a}}{T_a} \right)}{\dfrac{1}{F} \left[R_s + C \, V^n \left(P_o / P_B \right) N \right]} \qquad (13)$$

$$(27, 41)$$

In this process the environmental variables, T_a, P_B, P_{H_2O}, and V are all important in determining the rate. (Q, F, and C are constants, while R_s represents the resistance of the skin.)

In the case of evaporation:

$$E \cong C \, (P_{H_2O_s} - P_{H_2O_a}) \, (1 + V/k) \, (1 - P_B/K) \qquad (14)$$

$$(96)$$

where C is a constant dependent upon T_a, and k and K are also constants. In this process, also, the environmental variables T_a, P_B, P_{H_2O}, and V are all important in determining the rate. In both equations, many of the so-called constants are directly influenced by atmospheric gas composition, so that GC also plays a role in these processes.

The introduction by Mole (82) of the concept of relative humidity of the skin provided an expression of the water content of the surface layer of the skin expressed as a percentage of the maximum content, the maximum being a homogeneous thin layer of water over the entire surface. Peiss and Hertzman (92) speak of the skin R.H. as a measure of the relative amount of water available for diffusion and evaporation.

Changes in the rate of W_D can be caused by alterations in the R.H.

or state of hydration of the stratum corneum which are independent

of skin temperature, or by changes in the skin resistance to dif-

fusion.

Although the concept of skin relative humidity is a useful one

in talking about the amount of water available for IWL_S, it has been

pointed out that it fails to quantitate the mechanisms involved, and

is essentially an artifact whose value is determined by the evaporative

rate and the vapor pressure differences along the route of diffusion.

When only the W_M component of IWL_S is considered, one is dealing

with a glandular secretion whose production is not influenced by environ-

mental changes in T_a, P_B, P_{H_2O}, V, and GC. Only after secretion and

exposure to the ambient air do environmental factors influence its

disappearance from the human body through evaporation (equation 14).

Skin relative humidity and skin resistance to diffusion play no role

in the rate of water loss.

This is not the case with W_D, which must first diffuse to the

skin surface or to a water vapor-air interface in order to evaporate.

Ambient conditions of T_a, P_B, P_{H_2O}, V, and GC, influence W_D as it

diffuses and as it evaporates (equations 13 and 14).

In the case of W_M, the efficiency of evaporation may or may not

act as the rate-limiting step. In environments of low airflow, low

temperature, and high P_{H_2O}, water may be delivered to the skin surface

by eccrine glands at a rate greater than the maximum evaporative capacity

of the surrounding air. The water may then spread across the skin

surface and increase the area available for evaporation, may be absorbed

by the skin (diffuse into the epidermis), or may run off the skin.

If the evaporative capacity of the air is increased steadily, a

point will be reached where all of the eccrine secretion evaporates

almost immediately, and the efficiency of evaporation will no longer

be the rate-limiting step. Rather, the rate of secretion of water

will be rate-limiting.

In the case of W_D, a similar but more complex situation may prevail.

Here, both the rate at which water vapor reaches the skin surface

and the rate at which it can evaporate are extremely variable and are

regulated by environmental changes. Either step may be rate-limiting,

assuming that the rate of delivery of water is not always in excess

of the rate of evaporation. In some environments diffusion will

deliver a smaller amount of water vapor than the evaporative capacity

of the air can handle, and the diffusion process will be rate-limiting;

in other situations diffusion may deliver an amount of water vapor

that exceeds the evaporative capacity of the air, and the evaporative

process will become rate-limiting.

The accumulation of water within the epidermis because evaporation

is the rate-limiting process may be a very common phenomenon. As

discussed by Mole (82), the frequent observation that the wetness or R.H.

of the skin increases as the humidity of the air increases is related

to the fact that diffusion or secretion of water continues without

the water being added to the evaporative loss or running off the skin.

Mole goes on to hypothesize that, with constant convection and air

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temperature, an increase in air humidity will temporarily decrease
the loss of skin water vapor by evaporation until the continuing diffusion
of water from the tissues beneath the epidermis raises the skin humidity
and subsequently boosts the evaporative rate.

Although a division of the transfer of water from the epidermal
interior to the surrounding air into the two processes of diffusion
and evaporation may be an artificial one in some circumstances, it is
nonetheless a very useful one. The location of the liquid water-water
vapor interface may lie at various levels within the epidermis or
may lie on the skin surface, depending upon the R.H. of the skin, the
activity of eccrine and apocrine glands, the repenetration of water
into the skin, the evaporative capacity of the environment, and several
other factors (17).

The so-called barrier membrane located deep within the epidermis,
(principally at the levels of the stratum granulosum and stratum compactum
(89, 107), which inhibits the free flow of water to the surface, does
not necessarily demarcate the liquid-vapor interface. While diffusion
takes place through this barrier membrane, evaporation may commence
at any level at or above the membrane where a liquid-vapor division
occurs.

Barrer (6) has examined the manner in which diffusion through
solid membranes can take place, and has given the name "activated
diffusion" to the process by which a substance may diffuse through
the pores in a lattice of complex organic molecules. Such diffusion

is facilitated by temperature elevations, which increase the activity

of the diffusing molecule and increase the average pore size in the

membrane. Passage of water molecules through the barrier membrane

of the epidermis appears to fit the process of facilitated diffusion.

. The diffusion coefficient of the barrier membrane and its relation-

ship to water vapor pressure is still a matter of dispute. King (66)

demonstrated that, in the transport of substances through keratin

membranes, the diffusion coefficient itself can vary with the concen-

tration of the diffusing substance. The barrier zone of normal human

epidermis has also been shown to exhibit an absorption isotherm and

hysteresis effect in its interaction with water vapor. Mali (73)

has shown, however, that very little water is absorbed by the barrier

layer until an ambient R.H. above 70% is reached, and that the perme-

ability constant varies only slightly over a wide range of R.H. values.

The permeability of the barrier-zone epidermis of the trunk was roughly

proportional to the difference in P_{H_2O} between the two sides of the

membrane and inversely proportional to the thickness of the membrane.

This finding, as well as the water-vapor data accumulated in

the current study and by Zollner and Thauer (132), does not support

the contention that the effect of increasing P_{H_2O} on skin insensible

water loss is negligible because of an absorption isotherm in the

barrier membrane (50).

Subject-to-subject variations in IWL_S rates under identical envi-

ronmental situations are most likely related to differences in epidermal

structure, with resulting differences in permeability. No firm evidence for physiologic adjustment of permeability is available.

The efficiency of the water barrier zone of the epidermis varies considerably in different people and in different parts of the body, with significantly increased permeability in the palms and soles and minimum permeability in the chest and abdomen (92, 132). Some measurements indicate that the permeability of palmar skin to water is more than 20 times that of abdominal skin (92). This represents a decrease in barrier efficiency from 99.7% to 92.5% in its inhibition of free water passage.

Barrier efficiency drops even further when the skin is diseased and the architecture disrupted. In addition to thermal or chemical burns, diseases such as psoriasis, ichthyosis, and erythroderma may cause a 300% increase in skin insensible water loss (43, 54, 105, 108). In extreme cases, the loss of water through the skin may become life-threatening. In such cases, barrier efficiency may fall below 20% and water loss rates exceed 200 gm./m.^{2}/hr. (83, 107).

It is more difficult to relate intrasubject variations in IWL_S rates for replicate runs to changes in epidermal architecture or to changes in barrier membrane efficiency. Such intrasubject variations have been noted by other experimenters irrespective of measurement technics used (14, 50, 64, 88, 114). Since measurements occur only a few hours apart, one would not expect significant physical alterations within the skin in so short a time. These intrasubject changes in IWL_S rates, therefore, suggest that some physiologic adjustments could be

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acting to influence skin water loss within limits.

Fluid Balance Studies

The accuracy of any fluid - or weight - balance study rests almost
completely with the successful collection of all sources of weight loss
and the accurate measurements of all intake and output. A measure
of this accuracy is the closeness with which the values for total intake
and total output agree, taking into account changes in body weight.

In this study an average difference of 300 gm. was noted over the
first seven experiments with measured grand total outputs always lower
than total intakes. This lower-than-expected output can be accounted
for in several ways. In the first place, the grand total output is
computed from $W_0 + W_{e_1}$. As such, it includes all routes of weight
loss, both sensible and insensible, with W_G. Considering the average
activity of an experimental subject during a 24-hour period, W_G would
account for another 130 gm. of weight loss (table XI), bringing the
intake-output difference down to 170 gm.

In the second place, the rate of skin insensible water loss (W_{e_1}),
from which the 24-hour total IWL_S is computed ($W_{e_{1_t}}$), represents   the
rate of water loss associated with minimal metabolic activity   and
with the subject lying flat on the metabolic scale. Over the entire
24-hour period, the subjects actually averaged a greater degree of
activity, so one would expect their true value of $W_{e_{1_t}}$ to be higher
than that estimated from W_{e_1}. Some thermal sweating was noted, with
increased activity between measurement periods, substantiating the
rise in skin water loss.

The effect of total barometric pressure on almost all aspects of weight balance was not anticipated (table XXI). The consistent increase in total intake at 258 mm. Hg P_B and the consistent decrease in both urine-feces output and grand total output at this reduced pressure are similar to changes noted in acute mountain sickness. In the latter situation, however, reduced P_{O_2}, rather than reduced P_B, is thought to be the most important etiological factor (58, 80, 94, 106, 110). Multiple studies at the top of Pike's Peak, Colo. (alt. 14,100 ft.) have shown a near-normal or negative fluid balance in non-acclimatized subjects (36, 58, 80). Similar results were noted in athletes taken to the Andes for high-altitude training (31). In contrast to this, Galeotti and Signorelli (45) noted that subjects, in the Alps, demonstrated a positive water balance under resting conditions but a negative balance under active climbing conditions. The observations of Singh et al. (106) at altitudes from 11,000 to 18,000 ft. confirmed that subjects developing acute mountain sickness experienced a significant antidiuresis with weight gain during the first 6 to 96 hours of exposure.

In all of these studies hypoxia as well as reduced P_B were present, making it impossible to separate the individual effects of these two environmental factors. A negative water balance has also been noted on prolonged space flights of the Gemini and Apollo programs, where astronauts are subjected to weightlessness as well as to a lowered P_B (47, 48). An increased fluid output is accompanied by a decreased thirst, so that the fluid deficiencies are not made up.

The slight increase in total insensible water loss with reduced P_B noted in this study was attributable to the balancing of an increased IWL_S with a diminished IWL_R. If a reduced P_{O_2} had been present, then IWL_R would also have increased with reduced P_B, and IWL_T would have shown a marked increase.

As one would predict, a decrease in P_{H_2O}, with all other environmental parameters held constant, resulted in a significant increase in all sources of water loss and also in fluid intake (table XXI). The significant rise in IWL_T with falling P_{H_2O} was related to dramatic increases in both IWL_S and IWL_R. The increasing insensible water loss was accompanied by a decreasing loss of water through urine and feces.

With an increasing T_a one would also anticipate an increase in IWL_T because of an increase in both IWL_S and IWL_R. The increase in insensible water loss with rising temperature was also accompanied by a fall in sensible loss through urine and feces. The significant increase in fluid intake with a rise in T_a, despite the absence of thermal sweating, demonstrates the importance of temperature in estimating fluid requirements, no matter what the temperature range.

Of all the environmental factors studied, gas composition appeared to have the least effect on overall fluid balance (table XXI). Only IWL_S and, concomitantly, IWL_T were influenced by the substitution of He for N_2, and values for total intake and output were not significantly altered. Because of the similar physical properties of pure oxygen and oxygen-nitrogen mixtures, one would not expect to see differences in evaporative water loss or total water loss unless physiologic

adjustments played a major role. The effects of He on IWL_S and IWL_T can be related to its markedly different physical properties.

The attempt to calculate skin insensible water loss by the indirect approach of a weight-balance equation was not altogether successful. In the 27 experiments in which in which the calculation of W_{e2_t} was made, values of W_{e2_t} were almost always higher than the measured W_{e1_t} values. In only one instance, however, did the difference in the two determinations exceed 400 gm. In 24 of 27, the difference was less than 300 gm./24 hr.; in 19 of 27, less than 250 gm./24 hr.; and in 12 of 27, less than 200 gm./24 hr.

The higher rate of skin water loss determined through the use of the weight-balance equation may again reflect an actually higher average rate of skin water loss over a 24-hour period when the subject is not always in the resting state. Sweating during physical exertion would drive the skin water loss to a much higher level than would be anticipated from the resting measurements of W_{e1}.

The use of an indirect method of calculating skin insensible water loss would have broad application where elaborate equipment to measure IWL_S directly is not available or is not logistically usable. Caution must be exercised in the interpretation of these indirect results, however, since the influence of environmental variables on the rates of water loss is not as easily discerned with this method.

The relationship of environmental variables to respiratory water

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loss rates (IWL_R) has been explored since 1904, when Foa (as cited

in Marshall and Specht, 75) suggested that lung water loss was reduced

at high altitude. This finding was substantiated by Guillemard et

al. (55) in 1910. Galeotti and Signorelli (45) investigated the

effects of the temperature and humidity of inspired air and found

that increasing the inspired humidity significantly reduced the res-

piratory water loss. Newburgh and Johnson (87) concluded that respi-

ratory water loss was controlled simply by the environmental condi-

tions and by the lung ventilation rate. Other investigators (77,

124, 131) later showed that additional factors, such as the amount

of respiratory dead space and the transit time of air through the

lung, play a limited role in the determination of IWL_R.

Disagreement has been frequent as to whether the expired air

is saturated with water vapor. Measurements by Corlette (37),

Buettner (23), and Pfeiderer and Less (93) originally indicated that

this air was saturated. Studies by Seeley (104), Christie and

Loomis (33), Burch (29), and McCutchan and Taylor (77) all concluded

that the expired air was only 80% to 90% saturated for most ambient

conditions. A consideration of the data available has led most cur-

rent investigators to conclude that 100% saturation rarely occurs.

The data presented in this study, concerning the rates of IWL_R

and the influence of environmental variables upon these rates, are

in close agreement with the conclusions of other investigators (1,

29, 75, 131). The significant increase in IWL_R with a decrease

in ambient P_{H_2O} or an increase in T_a has been documented by McCutchan and Taylor (77), Burch (29), and Seeley (104). At low values of P_{H_2O} and high values of T_a, the inspired air is physically capable of picking up and holding more water vapor as it passes through the respiratory tract and approaches saturation. The quantity of water that can be added and held by the air is directly related to its degree of saturation before entering the lungs, since its saturation upon leaving the respiratory tract is held to 80% to 90%. Assuming a constant respiratory ventilation and a constant dead space and air transit time, the rate of respiratory water loss should be directly related to the R.H. of the inspired air, regardless of ambient temperature or water vapor pressure. Such a relationship was indeed observed in this study (fig. 25).

This relationship does not exist between skin insensible water loss and R.H. (fig. 26), where changes in T_a result in a shift of the y-intercept. It is clear that T_a has an important influence upon IWL_S rates – an influence separate from its effect on ambient air saturation.

The observations of Foa and others that IWL_R rates were reduced at high altitude have been recently amplified and quantified by Marshall and Specht (75) and by Wortz et al. (131). The later study concluded that decreases in minute volume with reduction in P_B account for the accompanying reduction in respiratory water loss. A further

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conclusion was that IWL_R, calculated in grams per liter of expired gas, did not vary with total pressure, while minute volumes decreased as much as 33% at 180 mm. Hg P_B. Rates of IWL_R fell from an average of 7.2 gm./m.^{2}/hr. at 760 mm. Hg, to 5.8 gm./m.^{2}/hr. at 180 mm. Hg P_B.

A significant reduction in minute volume at reduced P_B had been predicted by Jaeger and Otis (63) and Fenn (42) based on the fact that the work of breathing is reduced and the airway turbulence and resistance are lowered as the barometric pressure falls and atmospheric gases are rarefied.

In this study, pulmonary ventilation decreased by 10% from 538 to 485 liters/hr. with a decrease in P_B from 700 to 258 mm. Hg. This drop is smaller than would have been predicted from other work (131), possibly because of the mechanical resistance in the outflow circuit of the breathing apparatus with its large Drierite canister. The variations in rate of IWL_R with lower barometric pressure are directly proportional to this change in pulmonary ventilation, and also approximately a 10% reduction over the full range of T_a and P_{H_2O} measurements.

Total insensible weight loss, being composed of IWL_S, IWL_R, and IWL_G, may range from 500 to almost 1,100 gm. in a 24-hour period, even when thermal sweating does not occur. Thus, IWL_T may account for almost 50% of the total sensible and insensible body weight loss in a day, especially when a high T_a and V are combined with a low P_B

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and P_{H_2O}. Since a change in water vapor pressure from 14 mm. to 4

mm. Hg can result in a 300 gm./day increase in water loss, and a change

in ambient temperature from 20° to 8° C. can also cause a 300 gm./day

increase in insensible water loss, it is clear that environmental

variations which fall within or very close to the recognized "comfort

zone" can result in major alterations in body water balance if fluid

intake is not properly adjusted.

Although some investigators have stated that IWL_R usually com-

prises almost 50% of total insensible water loss, this figure was

found to be exaggerated in the current study. Skin insensible water

loss formed the major component of IWL_T under all conditions measured,

and never fell below 53% of the total. IWL_R accounted for as little

as 25.5% of IWL_T under environmental conditions featuring high P_{H_2O}

and low P_B and T_a, and increased to almost 44% under conditions of

low P_{H_2O}, high P_B, and average T_a.

It is important to recall that, although the influence of P_{H_2O}

and of T_a upon both IWL_S and IWL_R is in the same direction, the influence

of P_B on each of these two routes of insensible water loss is directly

opposite. At very low values of P_{H_2O}, IWL_S decreases so rapidly and

IWL_R increases so rapidly with increasing P_B that, at P_{H_2O} values

lower than those studied here, respiratory water loss should exceed

skin insensible water loss.

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Development of signs and symptoms:

Environmental criteria for human comfort, as established in the

ASHRAE index, indicate very little effect of relative humidity or

water vapor pressure, especially at their lower ranges. Only above

a 70% R.H. is the ambient temperature of maximum comfort shifted

slightly (2). A standard Aircraft Environmental Limit Chart (121)

establishes a "comfort zone" which includes R.H. down to 10%, and

environmental design charts developed for NASA have indicated an

"unimpaired performance zone" which includes water vapor pressures

as low as 5 mm. Hg (51). None of these environmental indices take

into account major changes in total pressure, atmospheric gas compo-

sition, or airflow (90).

In recent years, the United States Air Force has noted signifi-

cant dehydration, together with increased fatigue, in crews flying

multiple transpacific missions in high-flying pressurized aircraft

like the C-141. Discomfort and dehydration among the sick and in-

jured on medical evacuation flights have also been observed. A

cabin atmosphere which features a P_{H_2O} of less than 3 mm. Hg is a

feature of these aircraft, and nasal stuffiness, lip chapping, and

occasional eye irritation have been frequently reported. Such dis-

comfort also occurs on long flights on commercial jet liners.

Similar symptoms affecting the eye and nose have been reported

by American astronauts in Gemini and Apollo flights. A low-humidity

environment has been established in these spacecraft, but it is not

certain whether it is the low P_{H_2O} or the increased oxygen partial

pressure which is primarily responsible for the adverse effects.

Few serious attempts to quantitate the effects of environmental

variables on human sign and symptom development have been carried

out in these situations where environmental effects are prominent

(46). The use of any type of quantitative index to evaluate subjec-

tive and objective changes is fraught with difficulties. A clear

set of criteria for assigning numerical values to signs and symptoms

must first be established, and then observers must be trained to

relate these numerical values to signs and symptoms uniformly and

consistently.

In this study, careful training of subjects by medical experts

and repeated drilling with the subjective and objective evaluation

sheets did produce a high degree of uniformity and consistency.

This was reflected in the reproducibility of the data and the clear

trends which developed when environmental parameters were altered.

The finding that the subjective evaluation, or Symptom Index,

was more sensitive to environmental alterations than the objective

evaluation, or Sign Index, was not unexpected. An individual is

often able to notice subtle changes in his own feelings or health

before objective changes are apparent. A nose will feel stuffy

before marked mucosal edema is evident to others; a throat will feel

scratchy before significant inflammation develops. That the subject objective evaluations should be more sensitive than the physician objective evaluations was not completely anticipated, although several possible explanations for this phenomenon can be presented.

The final physician evaluation was performed some minutes after subjects emerged from the environmental chamber, and at this time the subjects, themselves, noted some improvement in signs and symptoms. Subjects were frequently aware of the symptoms claimed by the individual they were examining and could thus be biased in their evaluation of physical findings.(The physicians were not aware of the subjects' complaints.)

Total barometric pressure, water vapor pressure, and ambient temperature all exerted a significant effect on the development of both signs and symptoms in the experimental subjects. Although four studies were run substituting 100% O_2 and O_2:He atmospheres at 258 mm. Hg P_B, no significant alteration in the Sign Index could be detected. A small, but not statistically significant, increase in the Symptom Index in 100% O_2 and a small decrease in this index in O_2:He were noted, however.

A failure of the high oxygen atmosphere to be a significant augmenter of sign and symptom development has a number of explanations.

In the first place, one could conclude that it is the low humi-

dity rather than the O_2, itself, that is the culprit in artificial environments where dry oxygen is utilized. On the other hand, one may note that 100% O_2 atmospheres in this study provided a P_{O_2} of only 258 mm. Hg, which is just 60% greater than normal air and 44% greater than the $O_2:N_2$ atmosphere provided. If oxygen tensions had been higher, a more dramatic change in sign or symptom development might have been seen.

The interaction of P_B and P_{H_2O} in sign and symptom development is apparent in the 48-hour studies, alone, and in the grouped data for all experiments of 24-hour or longer duration. This interaction is of prime importance when one is selecting the minimum acceptable water vapor level for an environment in which the total pressure may be reduced; i.e., a spacecraft. Whereas at ground level, or 700 mm. Hg P_B, a water vapor pressure of 6.5 mm. Hg would be compatible with only a slight increase in signs and symptoms; at 27,000 ft., or 258 mm. Hg P_B, signs and symptoms would have increased markedly at 6.5 mm. Hg P_{H_2O}. At this reduced P_B, a P_{H_2O} no lower than 9 mm. Hg would be required to prevent this increase of subjective and objective abnormalities. This important effect of P_B is pointed out by the fact that the Symptom Index changes only from -0.64 to -0.68 when P_{H_2O} is reduced from 9 to 6.5 mm. Hg at 700 mm. Hg P_B. At 258 mm. Hg P_B, on the other hand, the Symptom Index jumps from -0.71 to -0.88 for this same fall in P_{H_2O}.

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The influence of ambient temperature upon sign and symptom development is mediated by direct thermal effects, as well as by drying of exposed surfaces. When the average skin temperature falls below 31° C., a clear sensation of cold usually develops; and when the T_s falls below 30° C., shivering usually ensues. At the opposite extreme, a sensation of uncomfortable warmth usually does not develop until the skin temperature rises above 35° C. (125).

At total pressure of 258 mm. Hg, the sign-symptom indices showed very little change over the ambient temperature range from 20° to 28° C. At ground level, or 700 mm. Hg P_B, however, a significant change in both the Sign-Symptom Index and the Symptom Index occurred between 24° and 20° C. Subjects complained of being cold at 20° C. only at ground level, and shivering was noted on a few occasions. An increase in nasal stuffiness with some coryza developed in most subjects – most likely a vagal response to feelings of coldness.

This major difference in response to the 20° C. environment at the two divergent total pressures is most likely related to the greater convective heat loss at 700 mm. Hg in a denser atmosphere. The average skin temperature at 700 mm. Hg P_B, 20.6° C. was as low as 29.9° C.; while at 258 mm. Hg P_B, 20.9° C., skin temperature averaged 31.5° C. Similarly the T_{ew} rose from 20.0° C. to 26.0° C. when P_B was changed from 700 mm. to 258 mm. Hg. The difference in the timecourse of symptom and sign development over 48 hours is

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most dramatically illustrated in the comparison of 14 mm. with 4

to 5 mm. P_{H_2O} atmospheres. At the elevated water vapor pressures,

the sign and symptom indices changed only slightly over the first

12 hours and then held at a constant level. At the extremely low

levels of P_{H_2O}, the indices changed rapidly through the first 20

hours of exposure and then remained remarkably constant. In almost

all cases, sign and symptom development was more rapid at 258 mm.

than at 700 mm. Hg P_B and plateaued at a greater level.

It is important to note that signs and symptoms did not continue

to develop or to worsen throughout the 48-hour exposure periods,

even at the very low levels of P_{H_2O}. The leveling off after the

first 20 hours may represent some small degree of adaptation or

acclimatization, but, at the same time, it is clear that there was

no tendency for signs and symptoms to diminish during the later hours

of exposure. A steady-state condition persisted until the experiments

were terminated; only one hour after termination, symptoms had already

decreased significantly.

Note must also be taken of the fact that sign and symptom develop-

ment did occur even at the high levels of P_{H_2O} (i.e., 14 mm. Hg,

R.H. 66%) where one would not expect it. This phenomenon is at least

partially related to certain features of the environmental chambers

in which the experiments were conducted. A fairly high noise level

was constantly present from large blowers and the environmental control

systems, and experimental subjects were forced to speak loudly to one another in order to make themselves understood. Because of the vocal strain, significant horseness and some throat irritation invariably developed in all experiments, irrespective of environmental conditions. In addition, the Beta-cloth covering of the metabolic scale and Beta-cloth sheets used on the beds caused some skin-itching, which was also reported on the subjective evaluation sheets.

Also, since the subjects were not advised, in advance, of the environmental conditions that they would be facing, there was probably a psychological attempt - either conscious or subconscious - to note some changes in their subjective or objective evaluations in order to please the investigators.

The analysis of signs and symptoms according to anatomical areas involved bringing several important points to light. In the data summaries from all experiments, the relative frequency-severity of 6 of the 9 anatomical categories differed greatly in respect to symptoms and signs. Whereas the subjects were most often bothered by nose problems, particularly stuffiness, nasal signs were reported less than signs involving the lips and eyes. On the other hand, while lip signs were most frequently noted, lip symptoms were reported by the subjects less than nasal symptoms. Only scalp, skin, and general categories maintained their same 7th, 8th, and 9th, positions in both the Sign Index and the Symptom Index.

It is interesting to note that nasal stuffiness, lip chapping,
and occasional eye-burning and tearing were the most frequent complaints
aboard jet aircraft, Apollo capsules, and often in forced-air heated
homes. These same signs and symptoms predominated in the current
study (table XVIII).

Signs and symptoms involving the nose, lips, and eyes were also
most dramatically affected by alterations in those environmental
parameters which increase the rate of skin insensible water loss.
This was particularly evident with a lowering of P_B or P_{H_2O}. Changes
in T_a were closely associated with symptom changes involving the
nose and tongue in one direction (with a lowering of the T_a), and
the lips and pharynx in the other (with a high T_a). Changes in gas
composition, particularly the 100% O_2 environment, were related to
increases in nose, pharynx, tongue, and scalp symptoms and to lip,
tongue, mouth, and skin signs.

The fact that the skin and scalp were least affected by environ-
mental changes may be related to the length of exposure. Nonkeratinized
surfaces, such as the eyes, nose, and lips, dry more rapidly, causing
a rapid increase in signs and symptoms. Perhaps if exposures had
been extended well beyond 48 hours, drying of skin and scalp would
have been more noticeable. In an intermediate position in terms
of sign and symptom development were the tongue, mouth, and pharynx.
These areas were exposed only indirectly to the ambient environment

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when air was inhaled, and thus did not experience the full drying effect of the atmosphere.

The failure to observe significant changes in sensory function as measured by the special vision, taste, and olfaction tests in many experiments may also be related to the lengths of exposure. Since visual acuity and olfactory changes were noted only in those studies where the most severe drying conditions existed and rates of IWL_S were maximal, an exposure period of longer than 48 hours might have brought out sensory changes at more intermediate conditions of P_{H_2O}, P_B, and T_a. That humidity levels affect the sense of smell or the production of odors has long been known in the air-conditioning industry, and several studies have suggested that high levels of P_{H_2O} increase olfactory sensitivity (68). Although tearing as measured by the Schirmer test was significantly decreased in three experiments featuring low levels of P_{H_2O}, the lack of reliability of this test makes any interpretation difficult (49).

Alterations in taste thresholds as measured by the gustometer were seen in varying environmental situations. Decreases in taste were seen in some experiments featuring either low P_{H_2O} or elevated T_a, all at reduced barometric pressure. On the other hand, the increase in taste noted in both experiments conducted in a helium atmosphere may cause speculation that the helium, itself, is responsible for this taste acuity. Whether this gas can facilitate

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the diffusion of substances through the pores of taste buds or act

in some way to "tune up" the taste apparatus is a matter for future

investigation.

The relationship of sign and symptom development to rates of

insensible water loss, especially skin insensible water loss, is

a positive one (fig. 47). In environments where IWL_S is low or only

moderately increased, however, increases in the Sign-Symptom Index

are small (fig. 48). This relatively small increment of sign and symptom

change may be related to the ability of exposed skin and mucous mem-

branes to adequately compensate for slower rates of water loss and

thus resist surface dehydration. Fluid may be transferred from the

underlying tissue at a sufficient rate to balance the surface losses.

As rates of skin water loss increase further, rehydration of surface

tissue may not keep up with the rate of loss, thus accelerating the

development of signs and symptoms. With rates of IWL_S greater than

8.5 gm./m.^{2}/hr., the Sign-Symptom Index increased markedly with

small increases in IWL_S rates.

In summary, it is clear that all five environmental parameters

examined in this study can exert a significant effect on skin and

total insensible water loss, on total fluid balance, and on subjec-

tive and objective measurements of comfort. One does not need to

seek extreme ambient conditions that lead to marked discomfort,

significant thermal sweating, or pronounced dehydration in order

to observe and quantitate these environmental influences. Even within the generally accepted "comfort zones," these influences are evident.

The quantitative analysis of routes of insensible water loss from the human body, as influenced by environmental variables, can be correlated with overall fluid balance and with sign and symptom development. In this way a true picture of man's interaction with his environment can be defined (52), and accurate predictions for differing combinations of ambient parameters can be accomplished. Such associated factors as fluid requirements, urine and feces output, water loads on air-conditioning equipment, and overall comfort and performance efficiency can also be predicted.

Although many questions remain unanswered as to the actual mechanisms of some types of insensible water loss, this does not in any way preclude their careful measurement and quantitation. An accumulation of data relating water losses to environmental changes will facilitate the development of a predictive equation to encompass these findings and may ultimately shed new light upon the mechanisms, ' themselves.

Having defined the influence of environment upon insensible water loss, fluid balance, and general comfort, one must next approach the question of physiologic regulation or adjustment of these functions. Does the state of hydration of the subject influence his rate of insensible water loss or his ability to adjust to a dry

environment? Do changes in peripheral blood flow or in fluid-electrolyte regulatory hormones have a measurable effect upon skin water losses?

These questions are particularly pertinent in light of the finding of significant variability in IWL_S rates in the same subjects under identical environmental conditions. This variability was apparent despite the fact that all subjects were consistently in normal fluid balance.

Previous attempts to document changes in IWL rates directly related to alterations in fluid balance or peripheral circulation have not been generally successful, however (3, 53, 95). Most of these studies have depended upon local injection of materials together with local measurements of water loss rates. Some preliminary studies (92) have indicated that posterior pituitary extract can alter the rate of diffusion of water through excised dog skin as it does in frog skin (5), but these investigations must be extended to in vivo systems and to humans before any conclusions should be drawn.

Although subject-to-subject variations in insensible water loss rates can be satisfactorily explained on the basis of structural differences which alter permeability, a ready explanation for intra-subject variation is not now available (9, 86, 120,130). When the role of physiologic changes within the subject in the determination of rates of IWL_S, overall fluid balance, and sign-symptom development

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has been defined, even more precise predictions of man's interaction with his environment can be achieved.

REFERENCES

1. Adachi, J., and S. Ito. Insensible perspiration through the skin and respiratory passages and compensating changes in cutaneous perspiration. J. Orient. Med. 21:103 (1934).

2. ASHRAE Handbook. New York: American Society of Heating, Refrigerating, and Air-Conditioning Engineers, 1963.

3. Baker, H., and A. M. Kligman. Measurement of transepidermal water loss by electrical hygrometry. Arch. Derm. 96:441-452, (1967).

4. Bard, P. Body temperature regulation. In Bard, P. (ed.). Medical Physiology, ch. 34, pp. 526-555. St. Louis, Mo.: C. V. Mosby, 1961.

5. Barker-Jorgensen, C. The amphibian water economy with special regard to the effect of neurohypophyseal extracts. Acta. Physiol. Scand. 22:7, (1950).

6. Barrer, R. M. Diffusion in and through solids. London: Cambridge, 1941.

7. Beaumont, W. van, and R. W. Bullard. Sweating: Direct influence of skin temperature. Science 147:1465-1467 (1965).

8. Belding, H. S., and B. A. Hertig. Sweating and body temperatures following abrupt changes in environmental temperature. J. Appl. Physiol. 17:103-106 (1962).

9. Benedict, F. G., and H. F. Root. Insensible perspiration: Its relation to human physiology and pathology. Arch. Intern Med. 38:1-16 (1926).

10. Bennett, C. A., and N. L. Franklin. Statistical analysis in chemistry and the chemical industry. New York: Wiley, 1954.

11. Benzinger, T. H. On physical heat regulation and the sense of temperature in man. Proc. Nat. Acad. Sci. USA 45:645-659, (1959).

12. Benzinger, T. H., A. W. Pratt, and C. Kitzinger. The thermostatic control of human metabolic heat production. Proc. Nat. Acad. Sci. USA 47:730-739 (1961).

13. Berenson, P. J., and F. H. Green. Human thermal comfort in helium-oxygen atmospheres. Tech. proposal LS-148 AiResearch Mfg. Co., Div. of Garrett Corp., Los Angeles, Calif., May 1965.

14. Bettley, R. B., and K. A. Grice. Transepidermal water loss and inactivating sweat glands. Brit. J. Derm. 77:627-638 (1965).

15. Blagden, C. Phil. Trans. 13:604 (1775). (From Newburgh, Physiology of heat regulation. Philadelphia: W. B. Saunders, 1949.)

16. Blank, I. H. Further observation on factors which influence the water content of the stratum corneum. J. Invest. Derm. 21: 259 (1953).

17. Blank, I. H. Factors which influence the water content of the stratum corneum. J. Invest. Derm. 18:433 (1952).

18. Bradhma, G. B., N. Thompson, and J. C. Reynolds. The use of a metabolic scale. J.A.M.A. 198:170-173 (1966).

19. Brebbia, D. R. Water vapor loss from the respiratory tract during outdoor exercise in the cold. J. Appl. Physiol. 11:219 (1957).

20. Brebner, D. F., D. Kerslake, and J. L. Waddell. Diffusion of water vapor through human skin. J. Physiol. 132:225-231 (1956).

21. Buettner, K. Diffusion of water vapor through small areas of human skin in a normal environment. J. Appl. Physiol. 14: 269-275, (1959).

22. Buettner, K. Neue physikalische Ergebnisse zuz Waerme und Wasserhaushalt. Wiener Med. Wochenschr. 94:373 (1944).

23. Buettner, K. Physikalische Bioklimatology, Probleme und Methoden. Leipzig: Akademische Verlagsgesellschaft MBH, 1938.

24. Buettner, K. Diffusion of water and water vapor through human skin. J. Appl. Physiol. 6:229-242 (1953).

25. Bullard, W. R. Continuous recording of sweating rate by resistance hygrometry. J. Appl. Physiol. 17:735-737 (1962).

26. Burch, G. E., and T. Winsor. Diffusion of water through dead plantar, palmar and torsal human skin and through toe nails. Arch. Derm. 53:39-41 (1946).

27. Burch, G. E., and T. Winsor. Rate of insensible perspiration locally through living and through dead human skin. Arch. Intern. Med. 74:437-444 (1944).

28. Burch, G. E., and T. Winsor. Relationship of total insensible loss of weight to water loss from skin and lungs of human subjects in a subtropical environment. Amer. J. Med. Sci. 209-226 (1945).

29. Burch, G. E. Rate of water and heat loss from the respiratory tract of normal subjects in a subtropical climate. Arch. Intern. Med. 76:315-327 (1945).

30. Burriss, W. L., et al. Study of the thermal processes for man-in-space. SS-3280. AiResearch Mfg. Co., Los Angeles, Calif. 1965.

31. Buskirk, E. R., and J. Mendez. Survival in cold and at altitude. Fed. Proc. 26:1760 (1967).

32. Calvery, H. O., J. H. Draize, and E. P. Laug. The metabolism and permeability of normal skin. Physiol. Rev. 26:495 (1946).

33. Christie, R. V., and A. L. Loomis. The pressure of aqueous vapour in alveolar air. J. Physiol. 87:35-44 (1932).

34. Clifford, J., D. Kerslake, and J. Waddell. The effect of wind speed on maximum evaporative capacity in man. J. Physiol. London 147:253 (1959).

35. Comparative efficiencies of various dehydrating agents for drying gases. Bureau of Standards J. Res. 12:241 (1934).

36. Consolazio, F., et al. Protein and water valances of young adults during prolonged exposure to high altitude (4,300 meters). Amer. J. Clin. Nutr. 21:154 (1968).

37. Corlette, C. E. On the calculation of heat and moisture dissipated from the body by respiration. Med. J. Australia 2:198 (1942).

38. Du Bois D., and E. F. Du Bois. A formula to estimate the approximate surface area if height and weight be known. Arch. Intern. Med. 17:863-871 (1916).

39. Eckert, E. R., and R. M. Drake. Heat and mass tranfer. New York: McGraw-Hill, 1959.

40. Epperson, W. L., et al. Observations on man in an oxygen-helium environment at 380 mm. Hg total pressure: III. Heat exchange. Aerospace Med. 37:457 (1966).

41. Felsher, Z., and S. Rothman. Insensible perspiration of skin in hyperkeratotic conditions. J. Invest. Derm. 6:271 (1945).

42. Fenn, W. O. The pressure-volume diagram of the breathing mechanism. In Boothby, W. M. (ed.). Handbook of respiratory physiology. Albuquerque, N. Mex. Lovelace Foundation for Medical Education and Research, 1954.

43. Frost, P., et al. Ichthyosiform Dermatoses: III. Studies of transepidermal water loss. Arch. Derm. 98:231 (1968).

44. Gagge, A. P. A new physiological variable associated with sensible and insensible perspiration. Amer. J. Physiol. 120: 277-287 (1937).

45. Galeotti, G., and E. Signorelli. Biochem. Z. 41:268, 1912.

46. Gaul, L., and G. Underwood. Relationship of dew point and barometric pressure to chapping of normal skin. J. Invest. Derm. 19:9 (1952).

47. Gemini Midprogram Conference, NSAS SP-121, MSC., National Aeronautics and Space Administration, Houston, Tex., 1966.

48. Gemini Summary Conference, NASA SP-138, MSC. National Aeronautics and Space Administration, Houston, Tex., 1967.

49. Gifford, S. R., et al. Keratoconjunctivitis sicca. Arch. Ophthal. 30:207-216 (1943).

50. Goodman, A. B., and A. V. Wolf. Insensible water loss from human skin as a function of ambient vapor concentration. J. Appl. Physiol. 26:203 (1969).

51. Green, F. H. Environmental design charts. AiResearch Mfg. Co., Los Angeles, Calif., 1962.

52. Gregersen, M. I. Total water balance: Thirst, fluid deficits and excesses. In Bard, P. (ed.). Medical Physiology, ch. 17, pp. 317-331. St. Louis: C. B. Mosby 1961.

53. Grice, K. A., and F. R. Bettley. The effect of skin temperature and vascular change on the rate of transepidermal water loss. Brit. J. Derm. 79:582-588 (1967).

54. Grice, K., and R. Bettley. Skin water loss and accidental hypothermia in psoriasis, ichthyosis, and erythroderma. Brit. Med. J. 4:195 (1967).

55. Guillemard, H. R., R. Moog, and G. Regnier. Compt. Rend. Acad. d. Sci. 149-1151 (1909).

56. Hale, F. C., R. A. Westland, and C. L. Taylor. Barometric and vapor pressure influences on insensible weight loss. J. Appl. Physiol. 12:20-28 (1958).

57. Hammond, W. A. Drierite and its applications, pp. 8-59. W. A. Hammond Co., Xenia, Ohio, 1958.

58. Hannon, J., K. Chinn, and J. Shields. Effects of acute high-altitude exposure on body fluids. Fed. Proc. 28:1178 (1969).

59. Herlocher, J. E., et al. Physiologic response to increased oxygen partial pressure: I. Clinical observations. Aerospace Med. 35:613 (1964).

60. Hertzman, A. B., et al. Regional rates of evaporation from the skin at various environmental temperatures. J. Appl. Physiol. 5:153-161 (1953).

61. Hurley, H. J., and W. B. Shelly. The human apocrine sweat gland in health and disease. Springfleid, Ill.: Charles C. Thomas 1960.

62. Ikeuchi, K., and Y. Kuno. Insensible perspiration through the skin. J. Orient. Med. 7:67 (1927).

63. Jaeger, M. D., and A. Otis. Effects of the compressibility of alveolar gas on the dynamics and work of breathing. SAM-TR-63-71, Oct. 1963.

64. Johnson, C., and S. Shuster. The measurement of transepidermal water loss. Brit. J. Derm. 81, sup. 4:40 (1969).

65. Kerslake, D., J. L. Waddell, and D. F. Brebner. FPRC Report 902. J. Physiol. 132:225 (1956).

66. King, G. Permeability of keratin membranes to water vapor. Trans. Faraday Soc. 41:479 (1945).

67. Krantz, P. Calculating human comfort. ASHRAE Jour. 12:68 (1964).

68. Kuehner, R. Humidity effects on the odor problem Trans. ASHRAE 62:249 (1956).

69. Kuno, Y. The physiology of human perspiration. London: J. and A. Churchill, 1934.

70. Lloyd, D. P. C. Average behavior of sweat glands as indicated by impedance changes. Proc. Nat. Acad. Sci. US. 45:410-413 (1959).

71. Lobitz, W. C., Jr., B. Holyoke, and D. W. Montagna. The epidermal eccrine sweat duct unit. A morphologic and biologic entity. J. Invest. Derm. 22:157 (1954).

72. Loewy, A., and W. Wechselmann. Zur Physiologie and Pathologie der Wasserwechsels und der Warmeregulation Seitens des Hautorgans. Arch. Path. Anat. 206:79 (1911).

73. Mali, J. W. Transport of water through the human dermis. J. Invest. Derm. 27:451 (1956).

74. Manhigh III, USAF manned balloon flight into stratosphere. AFMDC TR-60-16. Holloman AFB, N. Mex. Apr. 1961.

75. Marshall, L. H., and H. Specht. Respiratory water vapor at simulated altitude. Amer. J. Physiol. 156:299-310 (1949).

76. McCutchan, J. W., and C. L. Taylor. The effect of reduced barometric pressure upon evaporation and perspiration in nude resting man. WADC-TR-54-72. Wright-Patterson AFB, Ohio. Sept. 1954.

112

77. McCutchan, J. W., and C. L. Taylor. Respiratory heat exchange with varying temperature and humidity of inspired air. J. Appl. Physiol. 4:121-135 (1951).

78. McCutchan, J. W. Body evaporation during short exposures to various temperatures, humidities, pressures, and mass velocities. Trans. Amer. Soc. Heat. and Air-Cond. No. 1568 62:237-248 (1956).

79. McCutchan, J. W., and C. L. Taylor. A quantitative study of evaporation from the human body during short exposures to various temperatures, humidities, pressures and mass velocities. WADC Tech. Note 55-522. Wright-Patterson AFB, Ohio, 1955.

80. McDonald, R., and V. Kelley. Effects of altitude anoxia on renal function. Amer. J. Physiol. 154:193-200, (1948).

81. Miller, S. U. Increased human body water loss at reduced ambient pressure. Aerospace Med. 33:689-691 (1962).

82. Mole, R. H. Relative humidity of the skin. J. Physiol. 107:399-411 (1948).

83. Monash, S., and H. Blank. Location and reformation of the epithelial barrier to water vapor. Arch. Derm. 78:710 (1958).

84. Montagna, W. The structure and function of skin. New York: Academic Press, 1962.

85. NASA Manned Spacecraft Center, Personal communication, Houston, Tex.

86. Neumann, C., A. E. Cohn, and G. Burch. A quantitative method for the measurement of the rate of water loss from small areas, with results for finger tip, toe tip and postero-superior portion of the pinna of normal resting adults. Amer. J. Physiol. 132:748-756 (1941).

87. Newburgh, L. H., and N. W. Johnson. The insensible loss of water. Physiol. Rev. 22:1-34 (1942).

88. Ohara, K., M. Knodo, and J. Ogino. Fluctuations in insensible perspiration. Japan J. Physiol. 13:441 (1963).

89. Onken, H. D., and C. A. Moyer. The water barrier in human epidermis. Arch. Derm. 87;584 (1963).

90. Optican, A. W. Thermal tolerance and comfort in air-conditioned spaces. Aerospace Med. 41:208 (1970).

91. Patlak, C. S. A contribution to the study of diffusion of neutral particles through pores. Bull. Math. Biophys. 21:129-139 (1959).

92. Peiss, C. N., and A. B. Hertzmann. Kinetics of evaporative water loss from the skin. WADC-AFTR-6680, pt. 5. Wright-Patterson AFB, Ohio, Dec. 1951.

93. Pfeiderer, H., and L. Less. Klimatischen Ansprüche an die Atemwege des Menschlichen Körpers. Bioklimat. Beibl. 2:1, 1935.

94. Picon-Reatequi, E., et al. Effect of reducing the atmospheric pressure on body water content of rats. Amer. J. Physiol. 172:33-36 (1953).

95. Pinson, E. A. Evaporation from human skin with sweat glands inactivated. Amer. J. Physiol. 137:492-503 (1942).

96. Pinson, E. A., and W. H. Langham. Physiology and toxicology of tritium in man. J. Appl. Physiol. 10:108 (1957).

97. Pinson, E. A. Water exchanges and barriers as studied by the use of hydrogen isotopes. Physiol. Rev. 32:123 (1952).

98. Pi-Suner, J. Action of atmospheric pressure on latent thermolysis. Amer. J. Physiol. 129:440-441 (1940).

99. Randall, C. W. Quantitation and regional distribution of sweat glands in man. J. Clin. Invest. 25:761 (1946).

100. Richardson, H. B. The effect of the absence of sweat glands on the elimination of water from the skin and lungs. J. Biol. Chem. 67:397-411 (1925).

101. Robinson, S., E. S. Turrell, and S. D. Gerking. Physiologically equivalent conditions of air-temperature and humidity. Amer. J. Physiol. 143:21-32 (1945).

114

102. Rohwer, C. Evaporation from free water surfaces. U.S.D.A. Tech. Bull. 271:78 (1931).

103. Rosenberg, E. W., H. Blank, and S. Resnick. Sweating and water loss through the skin. J.A.M.A. 179:809 (1962).

104. Seeley, L. E. Study of changes in the temperature and water vapor content of respired air in the nasal cavity. Trans. Amer. Soc. Heat. and Vent. Engr. (ASRAE) 46:259 (1940).

105. Shahidullah, M., E. Raffle, and A. Rimmer. Transepidermal water loss in patients with dermatitis. Brit. J. Derm. 81:722 (1969).

106. Singh, I., et al. Acute mountain sickness. New Eng. J. Med. 280:175 (1969).

107. Spruit, D., and K. E. Malten. Epidermal water barrier formation after stripping of normal skin. J. Invest. Derm. 45:6 (1965).

108. Spruit, D., and K. Malten. Water vapor loss of psoriatic skin. Brit. Med. J. 6:180 (1968).

109. Sunderman, F. W. Persons lacking sweat glands: Hereditary ectodermal dysplasia of the anhidrotic type. Arch. Intern. Med. 67: 846 (1941).

110. Swann, H. G., et al. Negative water blance during exposures to low barometric pressure. Science 96:588 (1942).

111. Szczesniak, A. S., H. Sherman, and R. Harris. The percutaneous absorption of water. Science 113:293 (1951).

112. Taylor, C. L., and J. Marbarger. Some effects of extreme heat and humidity on man. Fed. Proc. 5:104 (1946).

113. Taylor, C. L., and K. Buettner. Influence of evaporative forces upon skin temperature dependency of human perspiration. J. Appl. Physiol. 6:113-123 (1953).

114. Thauer, R., W. Kaufman, and G. Zollner. Der Insensible Gewichts-verlust als Funktion der Umweltbedingungen. Pflueger Arch. Ges. Physiol. 261:183 (1955).

115. Thompson, N. Tubular reabsorption of secretion in human eccrine sweat glands. Clin. Sci. 19:95 (1960).

116. Treadie, B. E. Assessment of mean radiant temperature of indoor environments. Brit. J. Indust. Med. 22:58 (1965).

117. Treat, H. L. Determination of the specific heat, viscosity, and thermal conductivity of binary mixtures of non-polar gases. NASA PR-T743936, progress report. NASA, Houston, Tex., 1969.

118. Treat, H. L. The derivation of an equation for effective wall temperature. Personal communication, 1969.

119. Trolle, C. A study of insensible perspiration in man and its nature. Skan, Arch. f. Physiol. 76:225 (1937).

120. Vinson, C., et al. The nature of the epidermal barrier and some factors influencing skin permeability. Toxicol. Appl. Pharmacol. 7:7 (1965).

121. Waggoner, J. N., and W. L. Burriss. Environmental control of manned spacecraft for durations up to two weeks. Amer. Rocket Soc. J. 32:1019-1028 (1962).

122. Wang, C. C., S. Strouse, and M. Andersch. Metabolism of obesity: basal metabolism and insensible perspiration during a period of reducing weight. Arch. Intern. Med. 46:1002-1013 (1930).

123. Webb, P. Water vapor as a critical component in sealed cabins and pressure suits. In Wexler, A. (ed.). Humidity and Moisture, vol. 2, pp. 78-84. New York: Reinhold Publ. Corp., 1963.

124. Webb, P. Air temperatures in respiratory tracts of resting subjects in cold. J. Appl. Physiol. 4:378-382 (1951).

125. Webb, P., L. N. Garlington, and M. J. Schwarz. Insensible weight loss at high skin temperatures. J. Appl. Physiol. 11:41 (1957).

126. Welch, B. E., T. Morgan, and F. Ulvedal. Observations in the SAM two-man space cabin simulator: I. Logistics aspects. Aerospace Med. 32:583 (1961).

127. Welch, B. E., and W. G. Robertson. Effect of inert gases in cabin atmospheres. In Bedwell, T. C., and H. Strughold (eds.) Bioastronautics and the exploration of space, p. 255. Aerospace Medical Division (AFSC), Brooks AFB, Tex. 1965.

128. Welch, B. E., et al. Effect of ventilating air flow on human water requirements. Aerospace Med. 34:383-388 (1963).

129. Winslow, C. E., L. P. Herrington, and A. P. Gagge. Physiological reactions of the human body to various atmospheric humidities. Amer. J. Physiol. 120:288-299 (1937).

130. Winsor, T., and G. Burch. Differential roles of layers of human epigastric skin on diffusion rate of water. Arch. Intern. Med. 74:428-435 (1944).

131. Wortz, E. C., et al. Reduced barometric pressure and respiratory water loss. Tech. Doc. Report LS-136, AiResearch Mfg. Co., Los Angeles, Calif., Oct. 1964.

132. Zollner, G., and R. Thauer. Der Insensible Gewichtsverlust als Funktion der Umweltbedingungen. Seine Abhängigkeit von dem Wasserdampfdruck der Luft im Indifferenten Temperaturbereich. Pflueger Archiv. 258:58 (1953).

TABLE I

Classification of water losses from the human body

Sensible vs. insensible water losses	Common range of daily loss (gm.)
A. <u>Sensible</u> losses (liquid water)	1,100 to 7,600
Urine	1,000 to 2,000
Feces	100 to 500
Drooling and tearing	0 to 100
Vomitus	0 to 1,500
Significant thermal sweating (eccrine activity)	0 to 3,500
B. <u>Insensible</u> losses (vapor water)	600 to 2,650
Respiratory (expired air)	250 to 800
Light thermal sweating (eccrine activity)	0 to 400
Emotive (mental) sweating	100 to 500
Diffusional or nonsecretory skin losses	200 to 800
Metabolic gas exchange	50 to 150

C. Difficult to measure water losses

Thermal sweating (over general body surface)(W_T)
   Composed of sensible and insensible eccrine activity ($W_{T_s} + W_{T_i}$)

Emotive or mental sweating (over palms, soles, axilla, forehead)--a secretory (eccrine and apocrine) type of water loss (W_M)

Diffusional or nonsecretory skin loss (over general body surface)--a nonsecretory type of water loss (W_D)

Respiratory loss (expired air brought close to 85% saturation with water vapor) (W_R)

Metabolic gas exchange (not a true water loss, but represents the excess weight of carbon dioxide removed over the weight of oxygen absorbed during metabolism-- it becomes important only for total-body gravimetric measurements) (W_G)

Fluid balance equations:

$$W_Z = W_A + W_I - W_O - W_e + W_{O_2} - W_{CO_2}$$ Basic Balance Equation

$$W_{e_2} = W_A - W_Z + W_I - W_O + W_{O_2} - W_{CO_2}$$ W_{e_2} Indirect Skin IWL

$$W_{e_2} = \text{Mean } W_e/\text{hr.} \quad X \quad \text{duration (hr.)}$$ W_{e_1} Direct Skin IWL

TABLE II

Previous measurements of skin insensible water losses

Investigator		Date	Technique	Site of measurement	Skin IWL rates* $(gm./m.^2/hr.)$	In range of this study	Mean $\pm$ S.D. by techniques $(gm./m^2/hr.)$
THIS STUDY		1969	Whole body-gravimetric	---	6.00 - 15.00	---	---
Ikeuchi and Kuno	(62)	1927	Whole body-gravimetric	---	10.51	Yes	
Wang et al	(122)	1930	Whole body-gravimetric	---	10.95	Yes	
Kerslake et al.	(65)	1954	Whole body-gravimetric	---	12.40	Yes	10.97 $\pm$ 76
Brebner et al	(20)	1955	Whole body-gravimetric	---	10.80	Yes	
Thauer et al.	(114)	1955	Whole body-gravimetric	---	9.50 - 12.50	Yes	
Hale et al	(56)	1958	Whole body-gravimetric	---	10.18	Yes	
Kuno	(69)	1934	Dessic. capsule	Multiple	10.50	Yes	
Burch and Wilson	(26)	1946	Dessic. capsule	Multiple	9.78	Yes	
Peiss and Hertzman	(92)	1951	Dessic capsule	Multiple	9.50	Yes	10 69 $\pm$ 2 20
Buettner	(24)	1953	Dessic. capsule	Multiple	14.00	Yes	
Hertzman et al.	(60)	1953	Dessic. capsule	Multiple	9.48	Yes	
Blank	(17)	1952	Diff. chamber	Trunk	2.00	No	4 50 $\pm$ 3.50
Mali	(73)	1956	Diff. chamber	Trunk	6.00 - 8.00	Yes	
Felsher and Rothman	(41)	1945	CaCl bag	Abdomen	65.00	No	60 00 $\pm$ 7.00
Monash and Blank	(83)	1958	CaCl chamber	Abdomen	20.00 - 90 00	No	
Rosenberg et al.	(103)	1962	Electrohygrom.	Abdomen	1.50 - 2.40	No	
Spruit and Malten	(107)	1965	Electrohygrom.-air flow	Forearm	5.00 - 17.00	Yes	5 33 $\pm$ 4.90
Baker and Kligman	(3)	1967	Electrohygrom.-air flow	Trunk	2.00 - 4.00	No	
Goodman and Wolf	(50)	1969	Infrared analysis-air flow	Forearm	5 40 - 8 40	Yes	---
Neuman et al	(86)	1941	Gravimetric-air flow	Multiple	20 00 - 80.00	No	
Pinson	(95)	1942	Gravimetric-air flow	Trunk	6.00 - 12.00	Yes	30 30 $\pm$ 27 00
Burch and Winsor	(27)	1944	Gravimetric-air flow	Abdomen	58.00	No	
Bettley and Grice	(14)	1965	Gravimetric-air flow	Abdomen	3 50	No	

* Average rate or range of rates at 760 mm Hg P_B, 20 - 28°C. T_a

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TABLE III

Twenty channels of continuously monitored data (with subject on metabolic scale)

Measurement	Symbol	Number of channels	Sensitivity
Metabolic scale	W_e	1	$\pm$ 1.0 gm.
Skin temperature	$T_{1..7}$	7	$\pm$ 0.1° C.
Rectal temperature	T_R	1	$\pm$ 0.1° C.
Black-globe temperature	T_{BG}	1	$\pm$ 0.2° C.
Ambient temperature	T_a	2	$\pm$ 0.2° C.
Water vapor pressure	P_{H_2O}	1	$\pm$ 0.5 mm. Hg
Total pressure	P_B	1	$\pm$ 1.0 mm. Hg
Partial pressure N_2	P_{N_2}	1	$\pm$ 1.0 mm. Hg
Partial pressure O_2	P_{O_2}	1	$\pm$ 1.0 mm. Hg
Partial pressure He	P_{He}	1	$\pm$ 1.0 mm. Hg
Wind velocity	V	1	$\pm$ 20.0 ft./min.
Heart rate	HR	1	$\pm$ 3.0 b.p.m.
Respiratory rate	RR	1	$\pm$ 1.0 b.p.m.

TABLE IV

General data on seven test subjects

Subject	Age	Ident.	Wt (kg.)	Ht (cm)	BSA (m.^{2})	VC (liters)	FEV (liters)	V_E (liters/min.)	HCT	Hgb (gm.)	BUN	Creat (mg. %)	Na	K (mEq./liter)	Cl	CO$_2$	T$_3$ (ug %)	T$_4$
L B	19	B	74.65	185.9	1.98	5.48	4.30	9.2	47	15.5	12.5	1.2	147	4.5	103	26	29 3	7.8
W C	20	E	71 47	171.7	1.84	5.70	4.73	8.0	45	14.6	16.0	1.2	149	4.9	107	30	28 4	6.8
H D	19	A	72.42	183.4	1.94	6 02	4.62	7.8	46	14.8	16 0	1.4	145	4 2	105	29	28 9	7 1
K F	19	D', E	79 20	182.9	2 01	5.91	4.05	9.9	45	14.8	12.0	---	144	4.6	106	30	34 7	5 4
R H.	18	C	87.90	189.2	2.15	5.81	4.95	10.1	43	15.2	15.0	1.0	148	4.9	104	27	32 3	5 0
M K	18	F	77 77	186.7	2.03	6.02	4 84	8.7	46	15.1	16 0	1 2	150	4 7	104	30	32.9	6 3
P K	20	D(B, E)	61.94	169 5	1.72	4.40	3.65	6.7	48	16.2	22 0	1.4	149	4 8	105	28	36.1	4 1
Mean	19		75 05	181.3	1.95	5.62	4.59	8 6	45.7	15.2	15 6	1 2	147	4.7	105	29	31 8	6 7

TABLE V

Plan of insensible weight loss experiment

Period		Control	E X P E R I M E N T A L				Control
Part		1	2	3	4	5	6
Duration		10 Days	21 Days	21 Days	13 Days	6 Days	10 Days
Environmental conditions	Symbol						
Total Pressure (mm. Hg)	P_B	700	700	258	258	480	700 565
Gas Composition	GC	77% N_2 (540 mm. Hg) 23% O_2 (160 mm. Hg)	77% N_2 23% O_2	30% N_2 (78 mm. Hg) 70% O_2 (180 mm. Hg)	100% O_2 70% O_2 30% He	67% N_2 33% O_2	77% N_2 23% O_2
Ambient temperature (^{O} C.)	T_a	20 24 28	20 24 28	20 24 28	24	24	24 28
Water vapor pressure (mm. Hg)	P_{H_2O}	14	4 - 14	4 - 14	6.5 - 9	6.5 - 14	4 - 14
Air flow (ft./min.)	V	40	40 - 300	40 - 300	40	40	40

TABLE VI

Experiment Ident	Duration (hr)	PB (mm Hg)	PH2O (mm Hg)	Ta (°C)	Tew (°C)	V (ft/min)	G	C	Ts' (°C)	W1 (gm)	WO (gm)	W (gm)	VENT (liter/hr)	WR (gn/m²/hr)	WRt (gm)	We1 (gm/m²/hr)	We1t (gm)	We2t (gm)	Welt (gm)	~We2t (gm/24 hr)	IWLT (gm/m²/hr)	IWLT (gm/24 hr)	Number of Subjects
1A	48	700	14 4	20 6	20 6	49	1		29 9	4536 2	3471 4	-162 1	535	3 1	297 6	5 9	561 6	853 4	-391 8	-195 9	10 4	496 8	6
1B	48	700	13 8	23 9	24 5	48	1		31 6	4704 7	3018 1	+ 44.5	532	5 1	489 6	6 7	642 4	1372 3	-729 9	-364 9	13 3	636 0	6
1C	48	700	14 5	27 9	28 3	41	1		33 8	5062 2	3023 2	+513 6	540	6 2	595 2	9 8	915 2	1260 5	-345 3	-172 7	17 5	835 2	6
2J	48	700	14 6	24 1	24 3	43	1		31.3	4717.3	3427 9	+ 81 2	538	4 5	432 0	6 4	510 4	938 5	-322 5	-161 2	12 4	592 8	6
2H	48	700	8 2	24 4	24 6	50	1		32 1	4690 7	2988 9	+260 6	538	5 9	566 4	7 9	725 6	1171 4	-445 8	-222 9	15 3	752 0	6
2G	48	700	6 5	24 5	24 9	54	1		32 1	4839 0	3750 1	-534 1	538	7 4	692 6	8 0	766 1	1353 4	-586 8	-293 4	16 9	836 4	6
2F	48	700	5 4	24 4	25 2	49	1		32 1	4799 3	3694 7	-123 1	538	8.0	748 8	8 9	821 6	955 9	-134 3	- 67 2	18 4	874 4	6
2A	10	700	3 3	21 2	22 2	54	1		30 7				540	9 3	181 4	8 4					19 2	951 2	3
2C	10	700	9 0	20 1	21 6	54	1		30 3				480	8 8	171 6	8 4					18 7	898 8	3
2E	10	700	4 6	21 0	20 9	41	1		30 7				540	7 8	152 1	6 9					16 2	784 8	3
2P	10	700	14 2	28 2	29 2	49	1		33 3				480	6 6	128 7	9 1					17 2	744 0	3
2M	10	700	9 0	28 1	31 1	46	1		33 2				540	8.6	167 7	9 8					19 9	982 4	3
3J	48	258	13 9	23 4	27 0	46	2		32 0	4850 7	2823 1	+380 1	487	4 1	383 7	8 9	784 0	1376 8	-593 7	-296 9	14 5	674 4	6
3I	24	258	12 0	24 2	28 9	69	2		32 9	2133 3	1389 5	- 36 9	487	4 7	219 9	9 5	440 4	645 9	-205 5	-205 5	15 7	752 0	6
3H	48	258	8 4	23 5	28.2	46	2		32 6	4862 3	2976 9	-242.1	487	5 6	524 2	10 2	896 0	1857 7	-961 7	-480 8	17 3	836 4	5
3G	48	258	6 1	23 7	27 3	45	2		32 8	5214 9	3028 4	+336 9	487	6 6	617 8	10.8	999 2	1579 9	-580 7	-290 4	18 9	920 8	6
3F	48	258	4 2	24 1	28 2	43	2		32 7	5114 0	3066 4	+234 5	487	7 3	683 3	11 7	1077 6	1543 4	-465 8	-232 9	20 8	1065 2	6
3A	10	258	4 3	20 7	25 7	45	2		30 8				513	7 8	152 1	9 1					18 4	982 8	3
3C	10	258	8 9	20 9	25 6	45	2		30 9				463	6 1	118 9	8 1					15 7	679 2	3
3E	10	258	14 2	20 9	26 0	46	2		31 5				513	3 0	58 5	6 4					10 9	528 0	3
3P	10	258	15 0	28 1	33 1	48	2		34 4				463	5 4	105 3	10 3					17 4	751 2	3
3M	10	258	9 1	28 6	32 5	46	2		34 0				513	7 8	152 1	11 2					19 0	921 6	3
3K	10	258	4 8	28 5	32 0	46	2		33 8				463	8 8	171 6	12 3					22 6	1046 8	3
4A	24	258	6 2	24 0	28.4	66	3		32 9	2073 3	1632 9	-258 7	466	7 2	336 9	11 2	518 8	564 3	- 45 4	- 45 4	19 9	936 4	6
4B	48	258	8 9	24 1	28 7	68	3		32 7	4997 8	3144 9	+191 4	466	5 0	468 0	10 4	964 8	1391 8	-427 0	-213 5	16 9	787 2	6
4C	24	258	6 3	24 2	29 8	82	4		32 1	2041 8	1730 2	-496.7	500	6 2	290 2	8 8	409 6	673 4	-263 8	-263 8	16 5	768 0	3
4D	48	258	8 9	24 3	28 8	63	4		32 4	4789 0	3105 3	+194 7	500	5 5	514 9	8.5	782 4	1237 2	-436 8	-218 4	15 5	722 4	3
5C	24	480	13 9	24 2	27 0	53	5		32 4	2081 7	1569 1	-183.5	493	3 4	159 1	7 5	345 6	561 2	-215 6	-215 6	12 4	578 4	6
5B	24	480	9 0	24 3	27 0	61	5		32 5	1956 7	1758.5	-282 9	493	4 5	210 6	8.4	389 2	346 2	+ 43 0	+ 43 0	14 4	669 6	6
5A	24	480	4 4	24 4	27 2	63	5		32 8	2034 5	1624 4	-309.6	493	7 3	341 6	9 8	458 4	587 9	-126 5	-126 5	18.6	866 4	6
6B	48	700	13 4	24 3	27 0	80	1		31 9	4592.5	3590 6	-263 1	510	4 5	421 2	7 3	670 4	995 2	-324 8	-162 4	13 3	619 2	6
6C	24	700	13 9	28 4	30 5	82	1		34 1	2316 7	1438 8	+122 9	514	5 6	262 1	9 9	460 4	622 2	-161 9	-169 9	17 0	792 0	6
6D	24	700	11 5	24 3	27 2	59	1		32 1	1878 3	1619 2	-479 6	512	3 9	182 5	7 5	345 6	603 1	-258 3	-258 3	12 9	600 0	6
7A	24	565	5 5	23 8	27 2	66	1		32 4	2003 3	1893 9	-587 8	530	7 8	365 1	9 3	444.2	562 4	-149 1	-149 1	18 9	887 2	6
2XQRS	24	709	7 0	28 1	31.7	61 -340	1		32 3	1780 0	1845 2	-671 4	488	7 1	332 3	11 2	513 6	471 2	+ 42 4	+ 42 4	19 8	931 2	4
2YTVW	24	700	9 2	28.4	32 5	52 -348	1		32 5	2105 0	1798 4	-398.0	488	6 1	285 5	12 4	555 0	565 2	+ 10 3	+ 10 3	20 0	854 4	4
3XQRS	24	258	6 8	28 2	31.1	47 -295	2		32 7	2205 8	1439 9	-324 7	445	5 9	276 1	12 8	570 0	937 8	-387 9	-387 9	20 2	950 5	4
3YTVW	24	258	9 2	28 2	31 4	47 -302	2		32 7	2350 0	1331 3	+ 79 2	445	6 3	294 8	12 2	547 2	806 8	-259 8	-259 8	19 9	852 0	4

Key to TABLE VI

P_B	Range of ± 1 mm. Hg
P_{H_2O}	Range of ± 0.5 mm. Hg
T_a	Range of $\pm 0.5\,^{\circ}$ C.
T_{ew}	Range of $\pm 0.6\,^{\circ}$ C.
V	Range of ± 20 ft./min.

GC   Gas Composition

1 = 21% O_2, 79% N_2

2 = 70% O_2, 30% N_2

3 = 100% O_2

4 = 70% O_2, 30% He

5 = 33% O_2, 67% N_2

T_s Range of $\pm 0.1^{\circ}$ C.

W_I Total intake, liquids and solids

W_O Total output, liquids and solids (exclusive of W_{et} and IWL_G)

W   Change in subject weight during experiment

VENT.   Pulmonary ventilation with subject on metabolic scale (expired volumes measured)

W_R Respiratory insensible water loss (also IWL_R)

W_{Rt} Total W_R for an experiment (W_R x hours duration x B.S.A)

W_{ei} Skin insensible weight loss (IWL_S) measured directly on metabolic scale.

W_{eit} Total W_{ei} for an experiment (W_{ei} x hours duration x B.S.A.)

W_{e2t} Total IWL_S for an experiment calculated indirectly using weight balance equation (Table 1)

$W_{eit} - W_{e2t}$ Difference between W_e (IWL_S) calculated directly and calculated indirectly

IWL_T Total insensible water loss (= IWL_S + IWL_R + IWL_G), calculated from W_{Rt} + W_{eit} + W_{Gt}^*

$*\ W_{Gt} = W_{O_2} - W_{CO_2}$ x hours

TABLE VII

Controlled diet during study (per 24-hour period)

	Carbohydrates (gm.)	Fats (gm.)	Protein (gm.)	Total kilocalories
Basic diet.	375	114	95	2,811
Diet of subject C	421	124	108	3,152

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TABLE VIII

Subject weight changes during 12-week experimental period
(all weights in grams)

Subject	Initial weight	Final weight	Weight change	Average weight	S. D.*	S. E.*
A	71,775.0	71,369.0	-406.0	71,838.7	319.8	106.6
B	75,933.5	75,596.8	-336.7	75,459.8	596.0	210.7
C	87,930.7	87,817.2	-113.5	87,732.5	337.8	119.4
D	61,586.0	61,413.5	-172.5	61,241.0	619.6	234.2
E	69,574.0	72,690.0	+3,116.0	71,665.6	1,176.4	392.1
F	77,067.1	76,036.6	-1,030.4	76,763.7	553.0	195.5
Mean			+519.5			

* Subjects weighed at 7-day intervals during 12 weeks.

TABLE IX

Inspired gas volumes (liters/hr.) at representative ambient conditions

Exp. Ident.	P_B (mm. Hg)	P_{H2O} (mm. Hg)	T_a (°C.)	G C.	SUBJECTS							Mean (all subj.)	Mean -D'	Mean -D
					A	B	C	D*	D'*	E	F			
					Inspired gas volumes (to nearest 10 liters/hr.)**									
1A	700	14.4	20.6	1	480	550	610	430	590	490	540	527	517	543
1B	700	13.8	23.9	1	490	560	600	440	590	480	550	530	520	545
1C	700	14.5	27.9	1	470	570	600	440	600	490	530	529	514	540
700 mm Hg P_B Experiments Mean												529	517	543
3J	258	13.9	23.4	2	440	510	570	400	560	450	510	491	480	506
3F	258	4.2	24.0	2	450	510	560	400	---	440	520	480	480	496
258 mm. Hg P_B Experiments Mean												487	480	501
4A	258	6.2	24.0	3	420	510	550	410	---	430	500	470	470	482
4C	258	6.3	24.2	4	450	540	580	420	---	460	530	495	495	512
5C	480	13.9	24.2	5	460	530	560	430	---	460	510	491	491	504

* Did not participate in all experiments.
  See table VI for key.
** Corrected to ambient conditions

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TABLE X

Gas exchanges of subjects on metabolic scale

T_a (°C.)		A	B	C	D	D'	E	F	Mean	Mean -D	Mean -D'
	B. S. A. (m.^{2})	1.94	1.98	2.15	1.72	2.01	1.84	2.03	1.95	1.99	1.94
24° C.	O_2 cons. (liters/hr.)	15.70	16.00	16.90	14.50	16.30	14.90	16.60			
	CO_2 prod. (liters/hr.)	12.90	13.10	13.90	12.20	13.50	12.70	14.00			
	$O_2 - CO_2$ (gm./hr.)	-2.96	-2.80	-3.07	-3.16	-3.13	-3.51	-3.63	-3.20	-3.20	-3.20
	R. Q.	.83	.82	.83	.84	.83	.85	.85	.84	.84	.84
20° C.	$O_2 - CO_2$ (gm./hr.)	-3.05	-2.98	-3.22	-3.28	-3.27	-3.69	-3.77	-3.30	-3.30	-3.30
28° C.	$O_2 - CO_2$ (gm./hr.)	-2.87	-2.75	-2.86	-3.10	-3.01	-3.40	-3.52	-3.10	-3.10	-3.10

TABLE XI

Estimated average gas exchange for 24-hour experiment
(based on O_2 consumption of 25 liters/hr.)

T_a (^{0} C.)	R.Q.	$O_2 - CO_2$ (gm./hr.)	$O_2 - CO_2$ (gm./24 hr.)
20	.84	-5.41	-129.8
24	.84	-5.33	-127.9
28	.84	-5.25	-126.0

TABLE   XII

OBJECTIVE   EVALUATION

Area	1	2	3.	4	5	
EYES	NORMAL	Mild tearing	Moderate tearing	Mild Redness	Mod-severe redness	
NOSE	NORMAL	Mild edema/redness	Mod-severe edema/red	Crusting/cracking	Bleeding	
LIPS	NORMAL	Slightly dry	Moderately dry	Cracking/peeling	Bleeding	
TONGUE	NORMAL	Sl -Mod dry	Coated	Redness	Crusting/cracking	
MOUTH	NORMAL	Slightly dry	Moderately dry	Redness	Crusting/cracking	
PHARYNX	NORMAL	Slightly red	Mod.-severe redness	Cracking/edema	Exudate, bleeding	
SCALP	NORMAL	Mild scaling	Mod.-scaling	Severe scaling	Crusting/bristling	
SKIN	NORMAL	Sl dry/scaling	Mod dry/scaling	Severe dry/scaling	Cracking/peeling	
GENERAL	NORMAL	Slightly ill	Moderately ill	Very ill	Request termination	
OTHER		List signs from 1 to 5 and describe				

SUBJECTIVE   EVALUATION

	1.	2	3	4	5	6
EYES	NORMAL	Slight burning	Mild burning	Mod-burning/pain	Severe burning/pain	Blurring vision/other
NOSE	NORMAL	Slightly stuffy	Mod dry/stuffy	Coryza	Post-nasal drip	Obstruction/other
LIPS	NORMAL	Slightly dry	Mod dry/chapped	Severely dry/chapped	Cracking	Painful/burning/other
TONGUE	NORMAL	Slightly dry	Moderately dry, burning	Very dry/burning	Painful/sev burning	Loss of taste/other
MOUTH	NORMAL	Slightly dry	Moderately dry/burning	Very dry/burning	Painful/sev burning	Swelling/other
PHARYNX	NORMAL	Slightly dry	Moderately dry/burning	Very dry/diff swall	Painful/burning	Difficulty swallowing/other
SCALP	NORMAL	Mild itch	Moderate itch	Severe itch/burning	Severe burning	Tingling/other
SKIN	NORMAL	Slightly dry/itch	Moderate itch	Severely dry/itching	Cracking/painful	Burning/other
GENERAL	NORMAL	Slightly ill	Moderately ill	Very ill, uncomfortable	Request termination	- - - - - - - - - - - - -
OTHER		List symptoms from 1. to 6 and describe				

TABLE XIII

Effects of increases in environmental variables on changes in rate
of insensible water loss from the skin

Environmental Condition	Range	Change in rate of skin IWL			
		Qualifying Conditions	Mean	Range	Units
Ambient temperature (T_a)	$20^0 - 24^0$ C. $24^0 - 28^0$ C. $20^0 - 28^0$ C.	700 mm. Hg P_B 700 mm. Hg P_B 258 mm. Hg P_B	+ 0.27 + 0.72 + 0.45	+0.24 to +0.30 +0.66 to +0.81 +0 42 to +0.48	gm./m.^{2}/hr./l^0 C. T_a Same Same
Water vapor pressure (P_{H_2O})	4 - 14 mm. Hg	---	~ 0.27	-0.25 to -0.31	gm./m.^{2}/hr./l mm Hg P_{H_2O}
Total pressure (P_B)	258 - 700 mm. Hg	---	- 0.58	-0.55 to -0.63	gm./m.^{2}/hr/100 mm Hg P_B
Wind velocity (V)	50 - 300 ft./min.	$O_2:N_2$ atmosph.	+ 0.70	+0.61 to +0.84	gm./m.^{2}/hr /50 ft./min. V
Gas composition (GC)	70% O_2:30% N_2 100% O_2 70% O_2:30% He	258 mm. Hg P_B 258 mm. Hg P_B 258 mm. Hg P_B	0 + 2 00% -18.00%	N.A.	N.A.

TABLE XIV

Step-wise multiple regression analysis of the influence of physical factors
upon the rates of skin insensible water loss

Physical factor	Cumulative correlation coefficient		F Value*	T Value*	P Value*
T_{ew}	1	0.530	214.7	14.65	.001
P_{H_2O}	1➤2	0.591	146.6	− 7.52	.001
M.W. of gas	1➤3	0.618	11 2.4	5.40	.001
T_a	1➤4	0.636	91.43	4.34	.001
V	1➤5	0.655	77.40	3.79	.005
P_B	1➤6	0.684	59.94	− 2.72	.01

* Noncumulative values

TABLE XV

Individual subject bias (deviation from grand mean value for all subjects
in all experiments) in determinations of IWL_S and IWL_R

Subject	Number of experiments considered	Deviation from grand mean value $(gm./m.^2/hr.)$	
		IWL_S	IWL_R
A	26	-5.5%	-6.1%
B	26	+0.4%	+4.2%
C	26	+0.2%	+2.3%
D	20	+16.5%	+1.5%
D'	6	-5.6%	+7.7%
E	26	+3.3%	-3.8%
F	26	-14.3%	-5.1%

TABLE XVI

Variation in IWL_S measurements in the same subject with ambient conditions held constant

Subject	Experiment 1-B			Experiment 3-G		
	Mean* (gm./m.^{2}/hr.)	S.D.*	S.E.*	Mean* (gm./m.^{2}/hr.)	S.D.*	S.E.*
A	5.4	0.76	0.38	10.4	1.40	0.70
B	7.6	1.41	0.72	10.9	0.66	0.33
C	7.6	0.32	0.16	10.6	0.72	0.36
D, D'	6.9	0.73	0.37	12.8	1.21	0.61
E	6.3	0.84	0.43	10.9	1.52	0.75
F	6.1	1.02	0.51	9.1	1.11	0.54

* Forty-eight hour experiment; mean, S.D., and S.E. of four determinations of IWL_S for each subj(

TABLE XVII

Sign-symptom frequency-severity index values for experiments $\geq$ 24-hr. duration

P_{H_2O} (mm. Hg)	P_B (mm. Hg)	Symptom index	Signs (by subject)	Signs (by physician)	Sign-symptom index
14	700	-0.64	-0.26	-0.09	-0.33
14	258	-0.74	-0.38	-0.05	-0.39
14	Mean	-0.69	-0.32	-0.07	-0.36
11.5	258	-0.70	-0.38	-0.25	-0.44
9	700	-0.64	-0.34	-0.24	-0.38
9	258	-0.71	-0.42	-0.27	-0.46
9	Mean	-0.67	-0.40	-0.25	-0.44
6.5	700	-0.68	-0.35	-0.21	-0.41
6.5	258	-0.88	-0.52	-0.33	-0.58
6.5	Mean	-0.78	-0.43	-0.27	-0.49
5	700	-1.12	-0.59	-0.35	-0.68
4	258	-1.21	-0.73	-0.45	-0.79
4.5	Mean	-1.18	-0.66	-0.40	-0.74
Overall range		-0.20 to -1.22	-0.11 to -0.73	+0.03 to -0.47	-0.18 to -0.83
Overall mean		-0.79	-0.44	-0.24	-0.49

TABLE XVIII

Sign and symptom frequency-severity rank

Area	Rank	Greatest frequency
Symptoms		
Eyes	4	Slight burning
Nose	1	Slightly to moderately stuffy
Lips	2	Moderate chapping
Tongue	6	Slightly dry
Mouth	5	Slightly dry
Pharynx	3	Moderately dry
Scalp	7	Slight itch
Skin	8	Slight itch
General	9	Slightly ill
Signs		
Eyes	2	Mild to moderate tearing
Nose	3	Mild edema, redness
Lips	1	Moderately dry, cracking
Tongue	4	Dry, coated
Mouth	6	Dry, redness
Pharynx	5	Redness
Scalp	7	Moderate scaling
Skin	8	Slight scaling
General	9	Slightly ill

TABLE XIX

Summary of specific sensory tests

Test	Experiments with significant change	T_a	P_B	P_{H_2O}	GC*	Change	Sig. level (P)	Interpretation
Visual Acuity	2F	24.4	700	5.4	1	1.1	P < .01	Acuity significantly DECREASED
	3F	24.1	258	4.2	2	0.7	P < .05	Acuity significantly DECREASED
Schirmer Test	2F	24.4	700	5.4	1	- 6.0	P < .05	Tearing significantly DECREASED
	2YJVW	28.4	700	9 2	1	- 6.8	P < .05	Tearing significantly DECREASED
	3A	20 7	258	4.3	2	- 5 0	P < .05	Tearing significantly DECREASED
Gustometry	3F	24.1	258	4 2	2	-288.0	P < 01	Taste significantly DECREASED
	3H	23.5	.258	8.4	2	- 60.0	P < .01	Taste significantly DECREASED
	3P	28.1	258	15.1	2	- 23.0	P < .05	Taste significantly DECREASED
	3M	28.6	258	9.1	2	- 21.0	P < .05	Taste significantly DECREASED
	4C	24.2	258	6.3	4	+ 33 0	P < 05	Taste significantly INCREASED
	4D	24.3	258	8.9	4	+ 53.0	P < .05	Taste significantly INCREASED
Olfactometry	3G	23 7	258	6.1	2	+ 5.2	P < .05	Smell significantly DECREASED
	3F	24.1	258	4.2	2	+ 4 2	P < 05	Smell significantly DECREASED

* See table VI for key to GC
Index numbers, no units

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TABLE XX

Physical properties of gas mixtures, 300^0 K

Gas composition and %		Heat capacity (dimensionless)	Thermal conductivity (cal/cm-sec. ^{0}K x 10^6)	Viscosity (gm./cm-sec. x 10^6)
$O_2 : N_2$	23 : 77 (air)	3.50	63.2	184.1
$O_2 : N_2$	33 : 67	3.51	63.4	186.9
$O_2 : N_2$	70 : 30	3.52	64.2	198.4
O_2	100 -	3.53	64.8	207.1
$O_2 : He$	70 : 30	3.22	106.1	214.9

TABLE XXI

Effect of environmental parameters on total intake and output and their components
(Significance levels are shown)

Measurement	↑P_B	↑P_{H_2O}	↑T_a	Δ G.C.
		Ambient conditions		
Total intake (W_I)	↓ (<.05)	↓ (NS)	↑ (<.05)	↕ (NS)
Grand total output ($W_O + W_{e_{I_t}}$)	↑ (<.01)	↓ (<.05)	↓ (< 10)	↕ (NS)
Respiratory insensible loss (IWL_R)	↑ (<.05)	↓ (<.01)	↑ (<.02)	↕ (NS)
Skin insensible loss (IWL_S)	↓ (<.01)	↓ (<.01)	↑ (<.01)	** ↓ (<.05)
Total insensible loss (IWL_T)	↓ (<.10)	↓ (<.01)	↑ (<.01)	** ↓ (<.05)
Weight change ($W_Z - W_A$)	↓ (NS)	↕ (NS)	↑ (NS)	↕ (NS)

* ↑ indicates an increase, ↓ a decrease, and ↕ no change

** He compared with O_2 and N_2

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Fig. 1   Relationships of Difficult-to-Measure Water Losses. (See
           table I for symbol explanation). The horizontal dimensions
           are roughly proportional to the magnitude of each type of
           loss while the vertical dimensions have no importance. IWL_T
           (1) is composed of components 2, 7, and 3. As measured in
           this study, W_e (5) includes W_M and W_D since W_{T_i} (4) is ab-
           sent. The three sources of weight loss actually measured
           on the metabolic scale when W_R (3) is trapped are denoted
           by 6. In practice W_e or IWL_S is determined by subtracting
           3 and 7 from the total rate of weight change on the meta-
           bolic scale.

- 1
- IWL$_T$
- 7
- 2
- IWL$_S$
- IWL$_G$
- IWL$_R$
- 5
- W$_e$
- 3
- 4
- W$_{Ti}$
- W$_M$
- W$_D$
- W$_{O_2}$ – W$_{CO_2}$
- W$_R$
- 6

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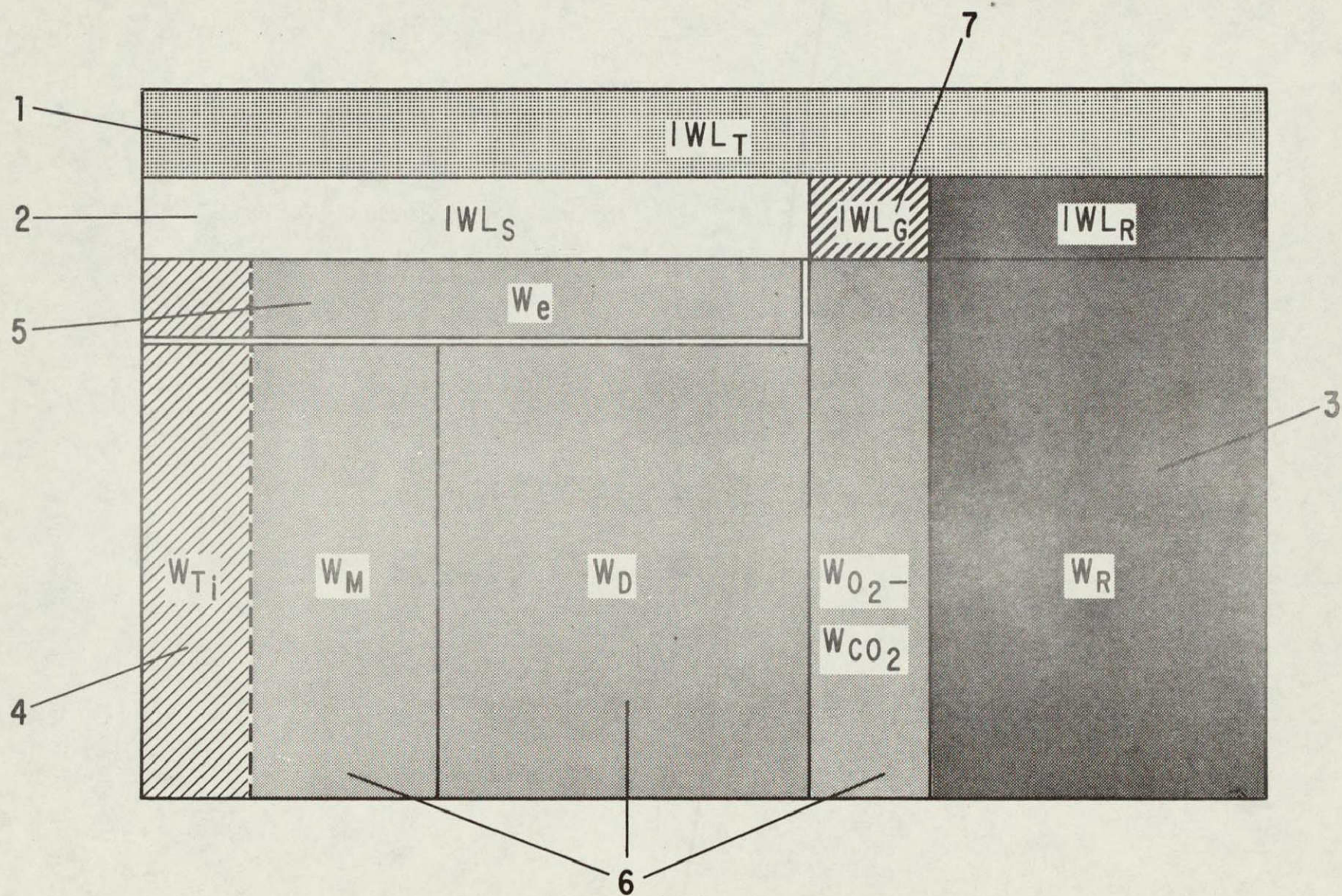
Fig. 2   Controlled Environmemtal Complex used in the study. Mea-
surements of insensible water loss rates were conducted
only in the laboratory section at left, while sleeping and
eating were confined to the test cell at right.

CONTROLLED ENVIRONMENTAL COMPLEX
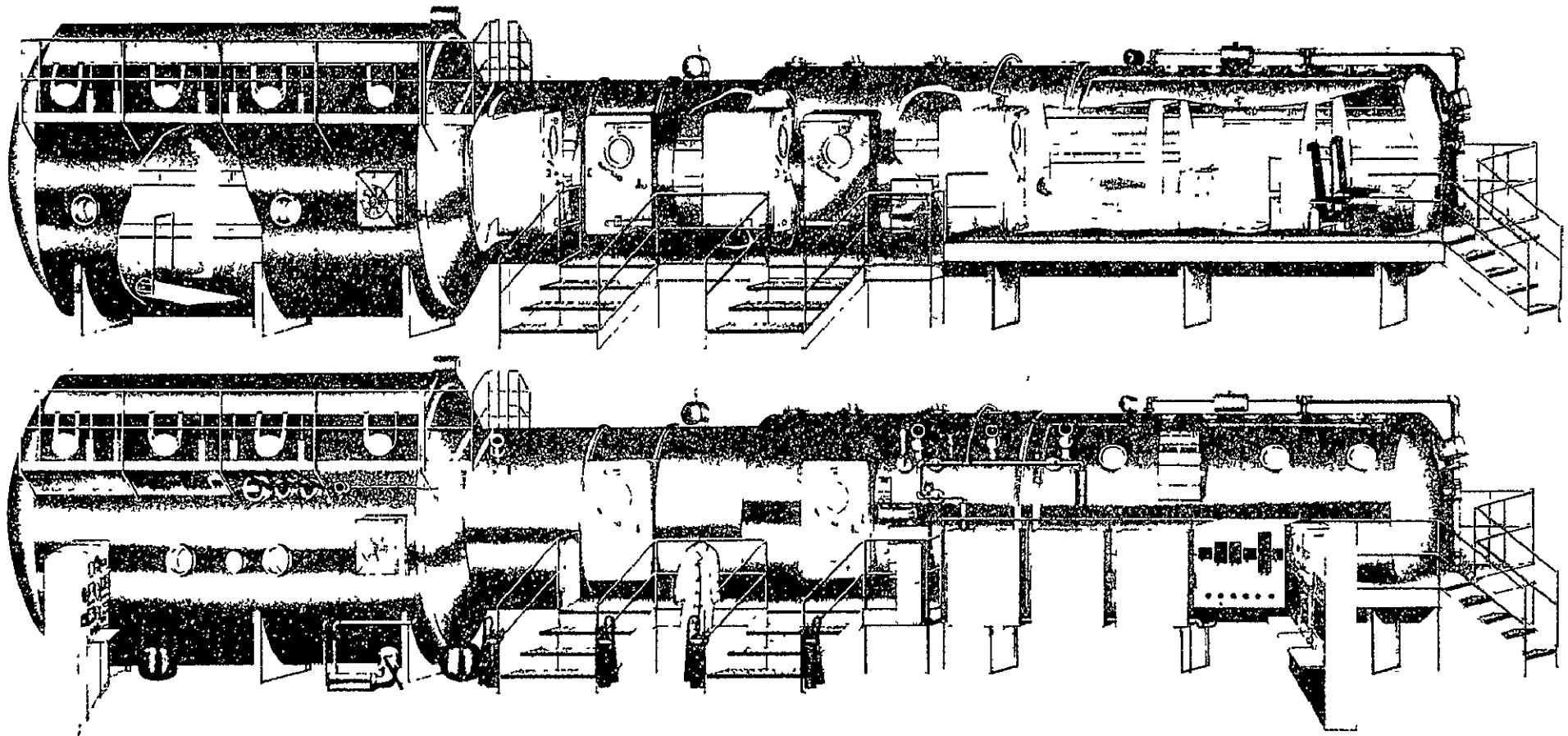
MISSION OBJECTIVES

- INVESTIGATE AND ESTABLISH PHYSIOLOGICAL LIMITS FOR MANNED ENVIRONMENTS APPLICABLE TO AIR FORCE REQUIREMENTS, E G AIRCRAFT AND SPACE CABIN ATMOSPHERES, AND MISSLE OPERATIONS

- FURTHER THE KNOWLEDGE BASE OF AEROSPACE PHYSIOLOGY THROUGH APPLIED RESEARCH.

- DETECT AND EVALUATE TRACE CONTAMINANTS GENERATED BY MAN WITHIN SEALED ENVIRONMENTS.

- OPERATE, MAINTAIN AND UPGRADE HYPOBARIC CHAMBERS AND ENVIRONMENTAL SIMULATORS TO PROVIDE A SAFE ATMOSPHERE FOR AEROSPACE RESEARCH

CAPABILITIES AND CHARACTERISTICS

- OVERALL CONFIGURATION
  - FOUR MAN TEST CELL (LIVING AREA)=950 CUBIC FEET.
  - LABORATORY= 2000 CUBIC FEET
  - SYSTEM OF AIRLOCKS AND PASSLOCKS FOR TRANSFERRING OF SUBJECTS OR EQUIPMENT
- ATMOSPHERIC CAPABILITIES
  - ALTITUDES-GROUND LEVEL TO 34 THOUSAND FEET
  - TEMPERATURE-35°-85°F
  - HUMIDITY-5mmHg WATER PRESSURE TO 100% RELATIVE HUMIDITY.
  - ATMOSPHERE-ANY GASEOUS MIXTURE OF O_2, CO_2, N_2, He, AND CO WITH 100% O_2 CAPABILITY. O_2, CO_2 AND N_2 ARE AUTOMATICALLY CONTROLLED
  - LIGHTING- DARK TO READING INTENSITY.
  - DATA-32 CHANNELS OF DIGITAL TELEMETRY UNITS

- SAFETY FEATURES
  - FIRE SUPPRESSION SYSTEM WITH AUTOMATIC UV DETECTION WITHIN 200 MILLISECONDS OR MANUAL ACTIVATION FULL WATER FLOW OF 75 GALLONS PER MINUTE PER SQUARE FOOT WITHIN 700 MILLISECONDS OF DETECTION
  - SMOKE, OVERHEAT AND ELECTRICAL FAULT DETECTION RAPID RECOMPRESSION FROM 34 THOUSAND FEET TO GROUND LEVEL IN 24 SECONDS.
  - ALL INTERNAL EQUIPMENT AND MATERIALS NON-COMBUSTIBLE
  - EMERGENCY POWER FOR LIGHTING AND COMMUNICATIONS

- EXPERIMENTAL CAPABILITIES
  - LABORATORY-ADDITIONAL MEASUREMENT EQUIPMENT AS REQUIRED BY THE EXPERIMENTAL PROTOCOL.
    - TREADMILL
    - ERGOMETER
    - METABOLIC SCALE
    - WIND TUNNEL
    - REBREATHING SYSTEM

Fig. 3   Sensor and equipment positions for measurement of the skin
         and respiratory components of insensible water loss. Pro-
         portionality constants for determination of the weighted
         average skin temperature (T_S) are shown.

SKIN TEMPERATURE SENSORS AND
PROPORTIONALITY CONSTANTS

T_1 (.07)

T_7 (.35)

T_2 (.14)

T_3 (.05)

T_6 (.19)

T_5 (.13)

T_4 (.07)

MASK-DRIERITE
SYSTEM

RESPIRATORY
RATE SENSOR

EKG SENSORS

SENSORS FOR
T_a, T_{BG}, V
LOCATED
ABOVE SUBJECT

β-CLOTH BRIEFS

SCREEN PLATFORM
WITH WOVEN
β-CLOTH COVER

DIRECTION OF AIR FLOW
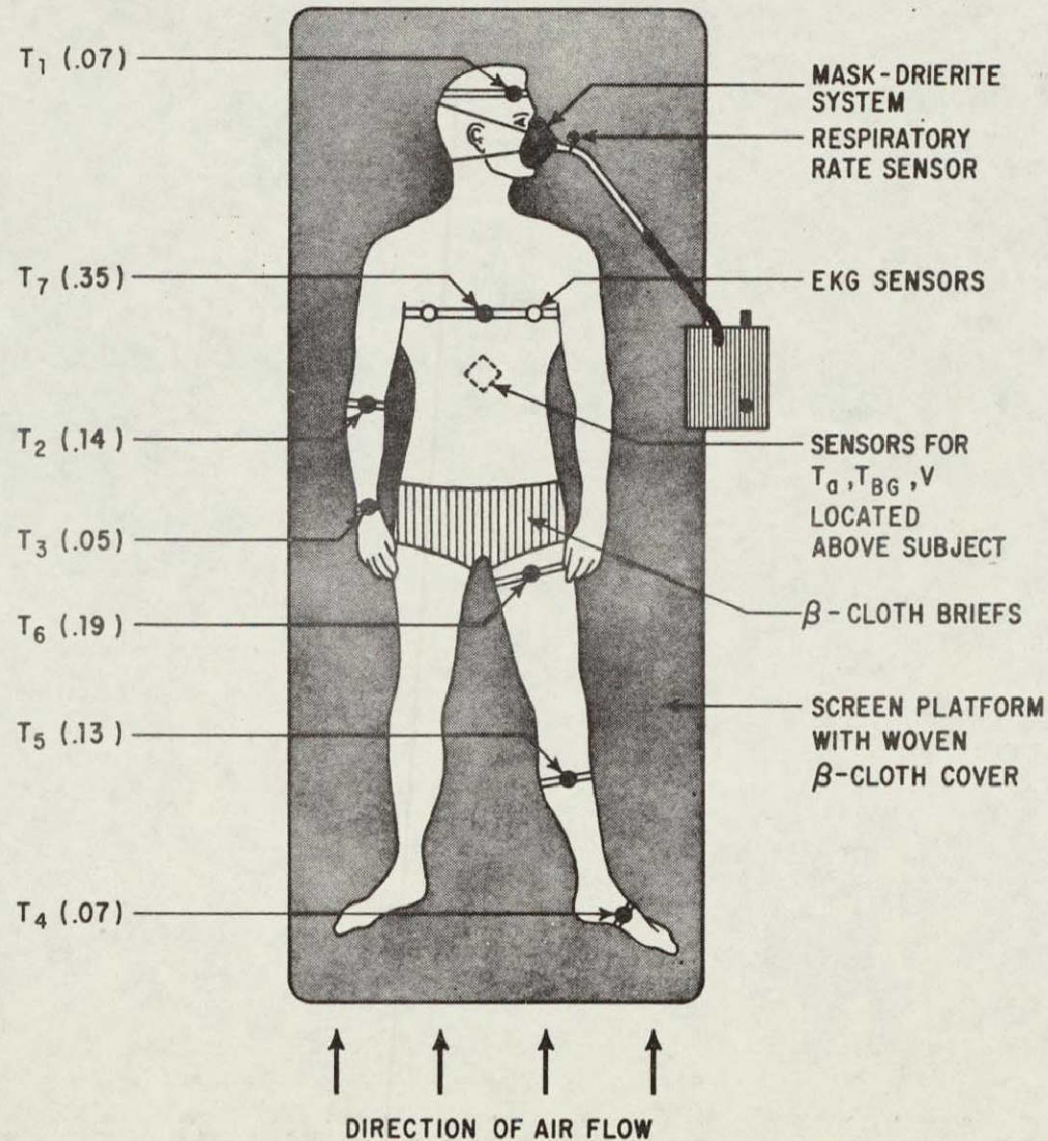
-145-

Fig. 4 Plan of typical 24-hr. experiment. Measurements of IWL_S and IWL_R were repeated three times at approximately eight-hour intervals on the metabolic scale ("2" on plan). Two rehydrated meals and two sleep periods ("12" and "11") were included.

24 HOUR EXPERIMENT

TIME 0700 0900 1100 1300 1500 1700 1900 2100 2300 0100 0300 0500 0700 0900 1100 1300 1500 1700 1900
       -4   -2   0   2   4   6   8   10   12   14   16   18   20   22   24   26   28   30   32

SUBJECT A

SUBJECT B

SUBJECT C

SUBJECT D

SUBJECT E

SUBJECT F

4-MAN OBSERVER #1

SYMBOL	TIME ALLOWED	KEY EVENT
⊞10½		TIME IN FOUR MAN CHAMBER
▨		SLEEP
⊟12	45"	REHYDRATED MEAL
⊙13	45"	NORMAL MEAL (BOX LUNCH)
1	15"	TOTAL BODY WEIGHT
2	60"	EVAPORATIVE WATER LOSS
3	15"	PHYSICIAN MED EVAL
4	4"	SUBJECT OBJ EVAL
5	2"	SUBJECT SUBJ EVAL
6	5"	GUSTOMETRY OLFACTOMETRY
7	10"	SHIRMER TEST VISUAL ACUITY
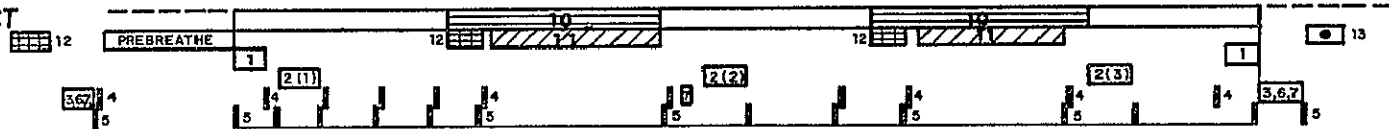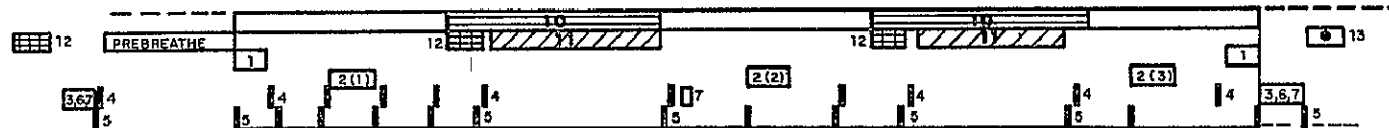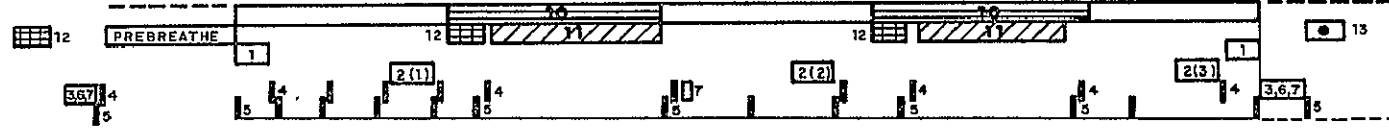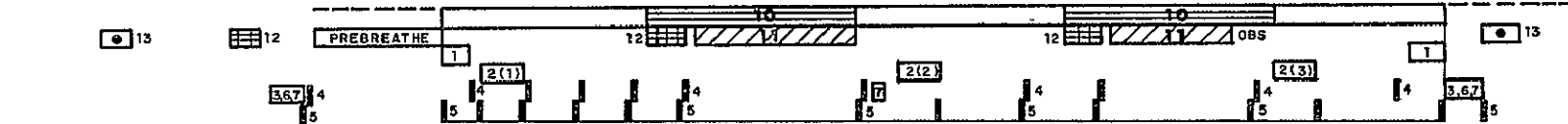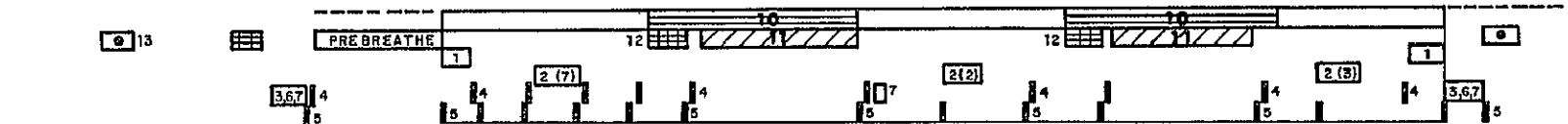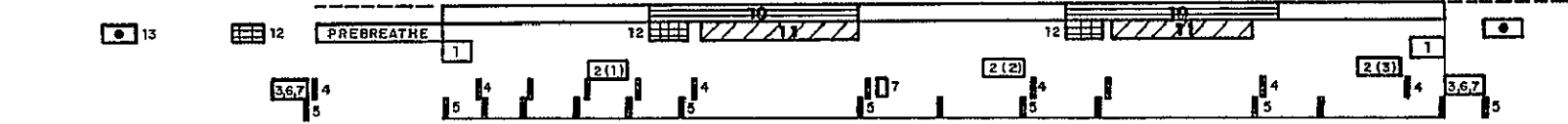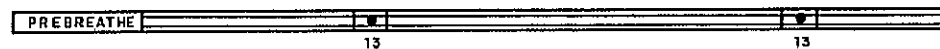
Fig. 5   Relationship of skin insensible weight loss to total baro-
metric pressure (P_B) and water vapor pressure (P_{H_2O}) at
24° C. T_a and V below 100 ft/min. Pressures are expressed
in mm. Hg. Significance levels for pressure differences
are shown.
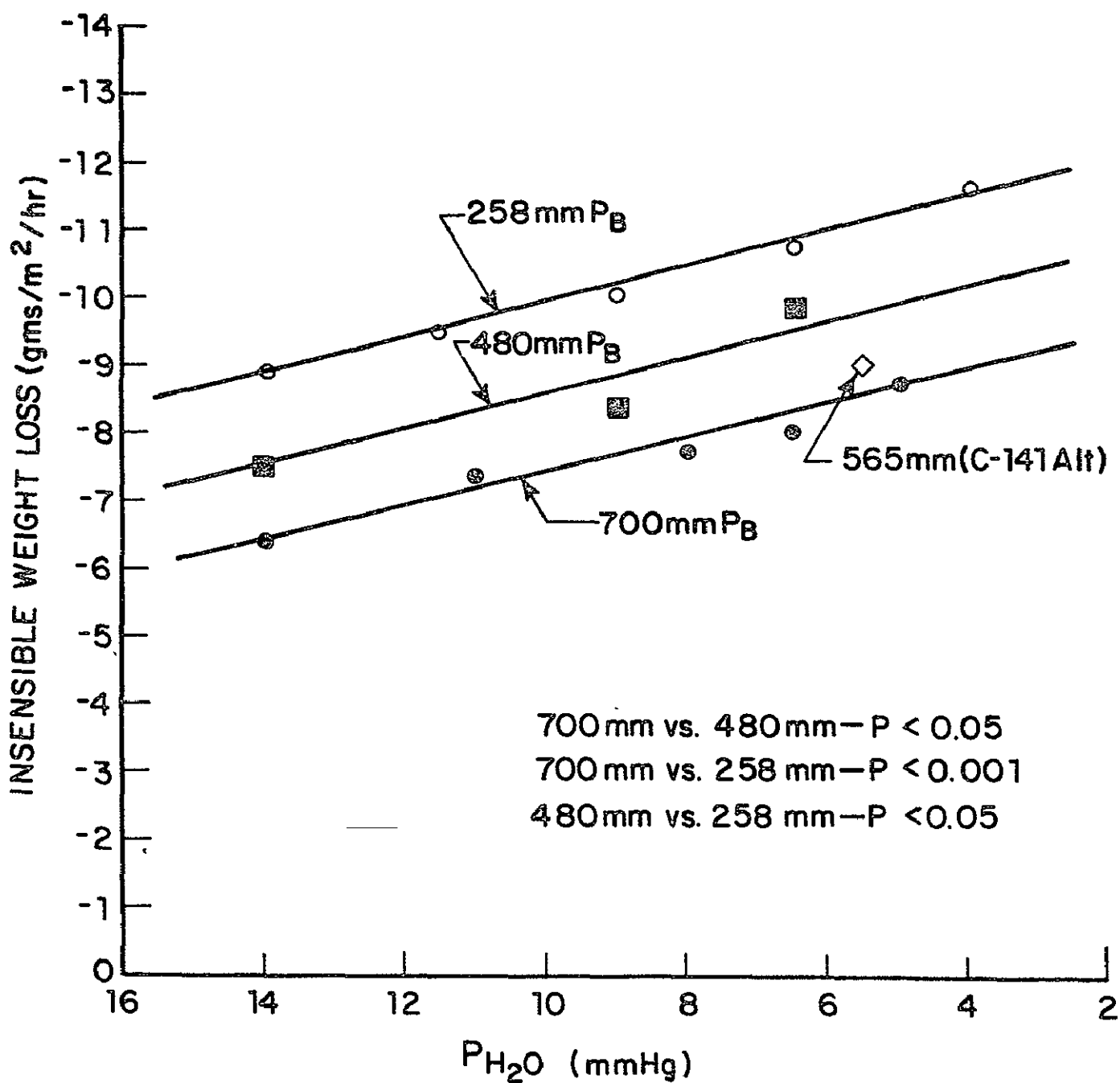
Fig. 6   Mean and standard deviations of skin insensible weight loss
values collected on six subjects at two levels of P_B and
five levels of P_{H_2O}.   (Compare with Fig. 5).
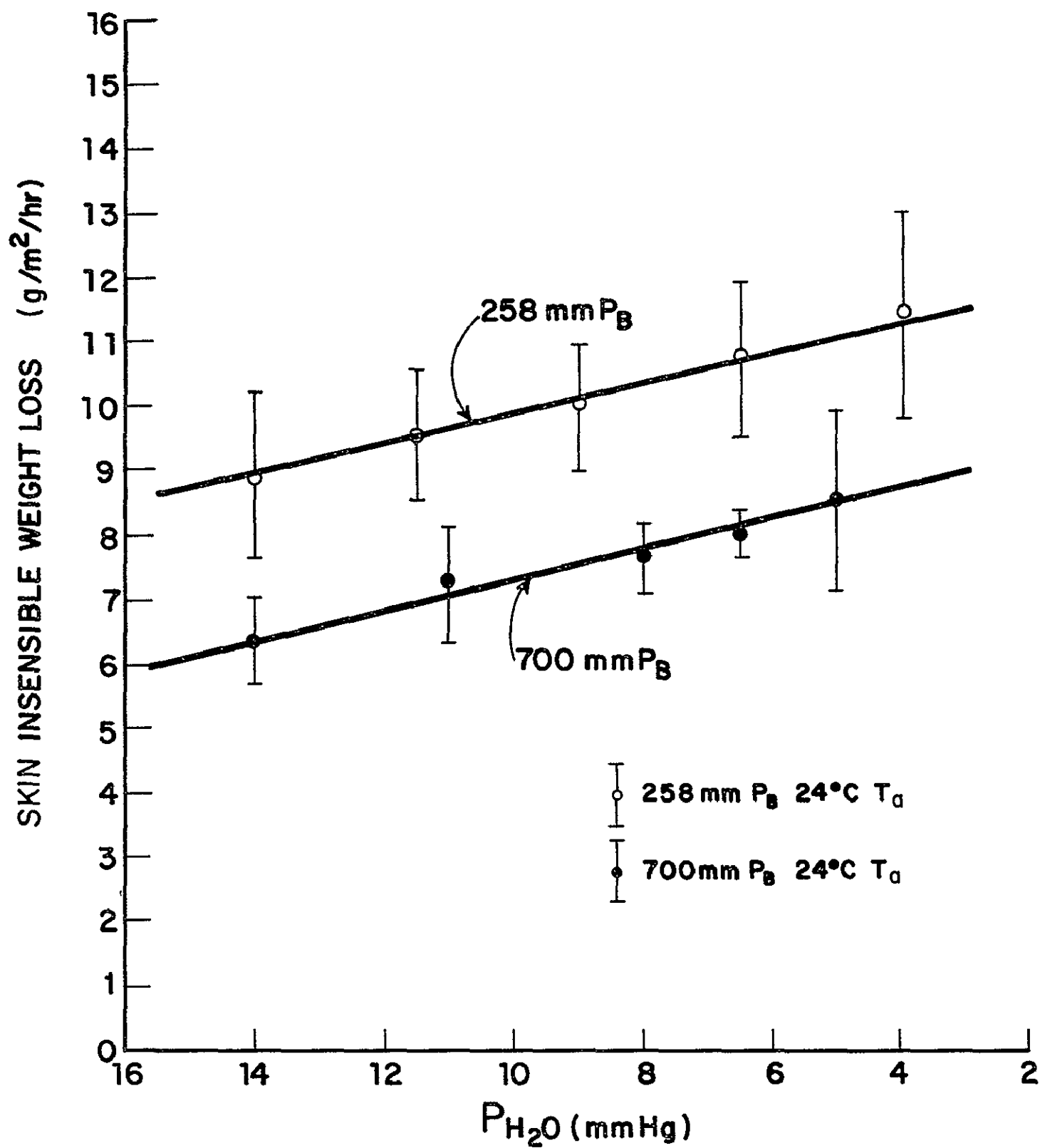
Fig. 7   Total range and mean of skin insensible weight loss values
          collected on six subjects at two levels of P_B and five
          levels of P_{H_2O}. (Compare with Fig. 5).
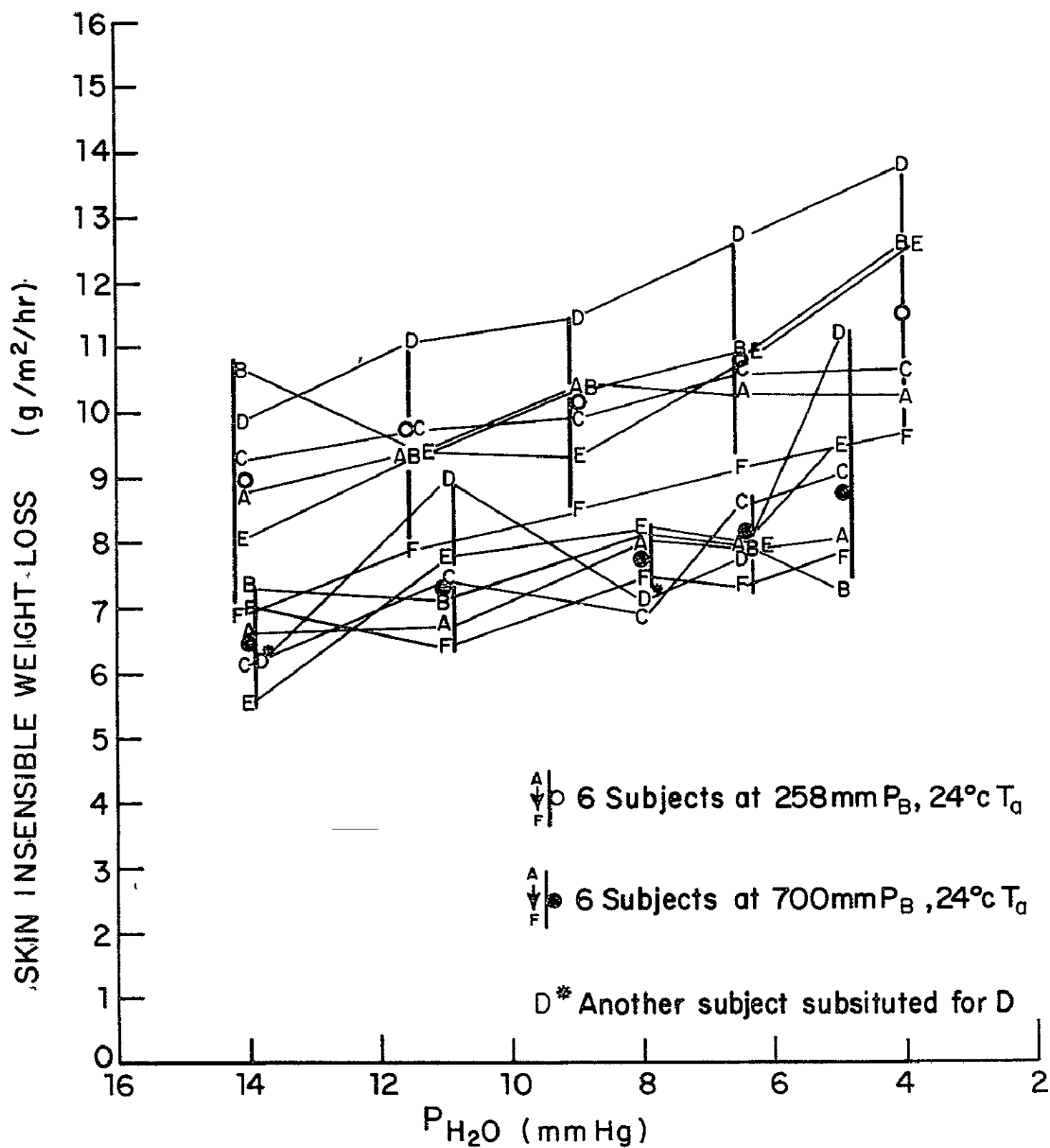
Fig 8. Relationship of atmospheric gas composition to skin insensible weight loss rates at 258 mm. Hg P_B, 24° C. T_a. Note the marked decrease in rate of water loss when He is substituted for N_2. Significance levels are shown.

70:30 O₂:N₂vs 70:30 O₂:H_e- P= <0.1

70:30 O₂:N₂ vs 100% O₂ - P= N.S.

70:30 O₂:H_e vs 100% O₂ - P= <0.1
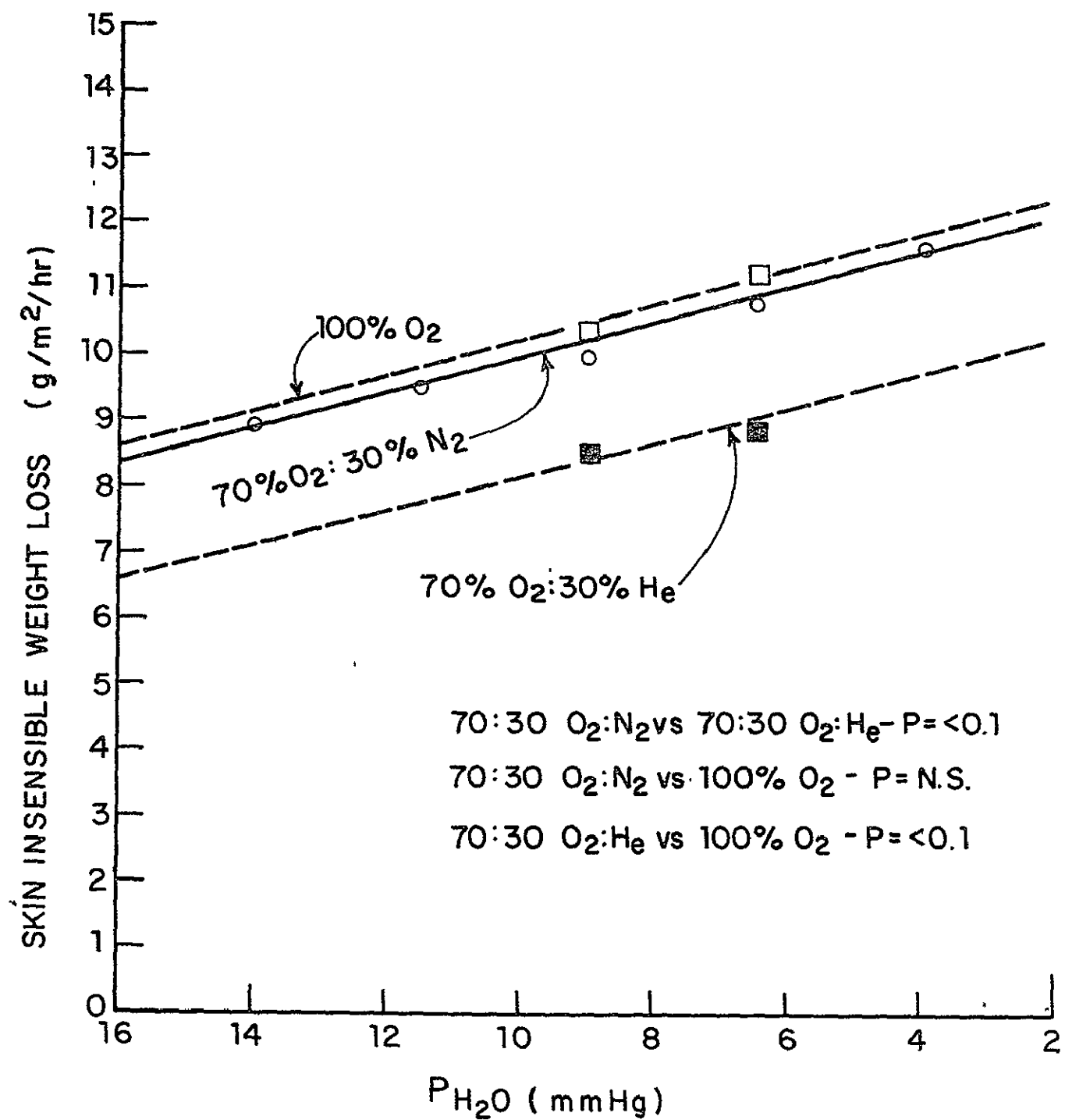
Fig. 9   Relationship of ambient temperature (T_a) to rates of skin insensible weight loss at varying P_B and P_{H_2O}. Note the significant effect of P_B with a non-linear relationship 'occurring at 700 mm. Hg P_B. Significance values are also shown.
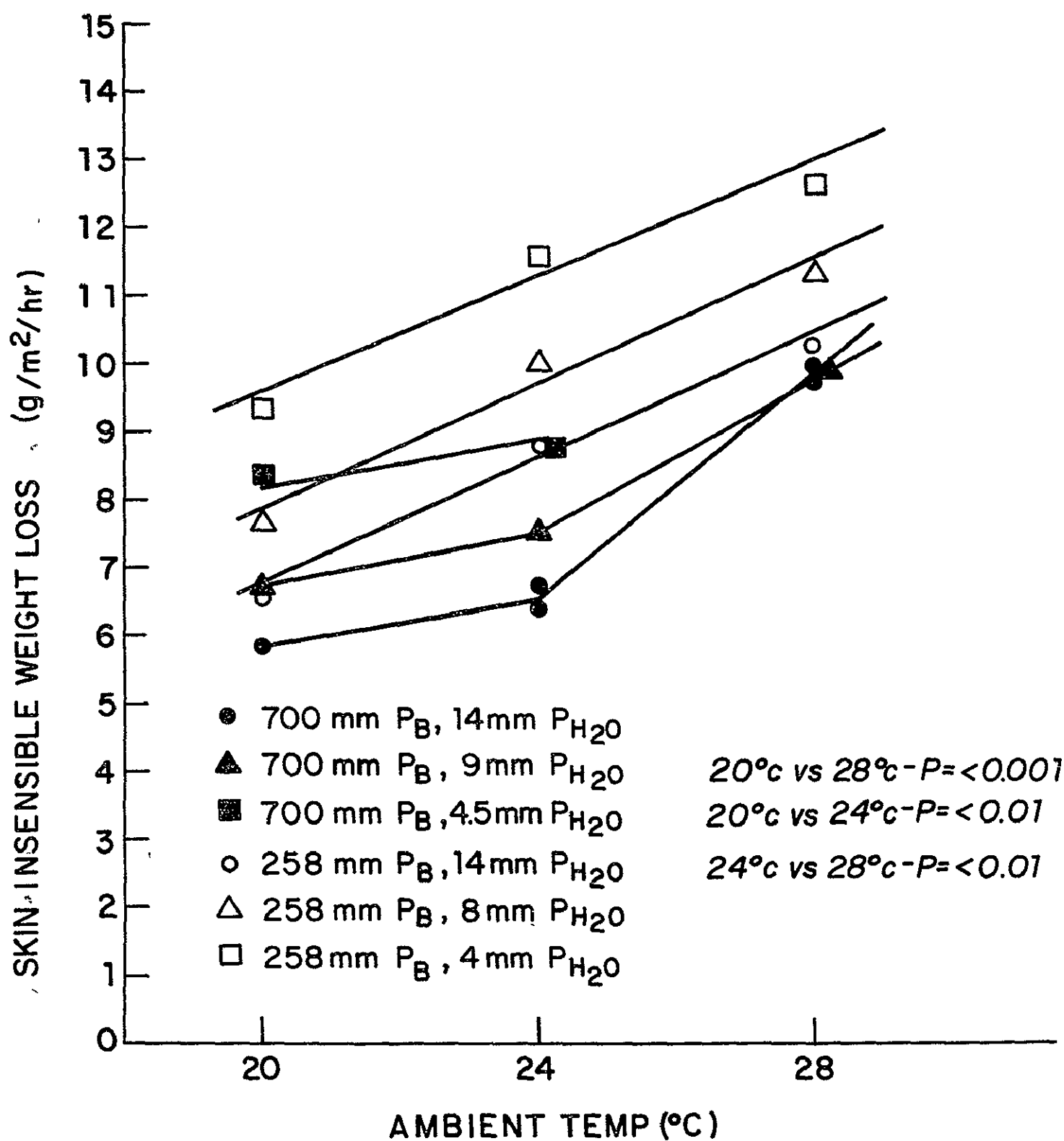
Fig 10   Mean and standard deviations for skin insensible weight loss
          rates in subjects exposed to varying T_a, P_{H_2O}, and P_B. The
          interaction of total pressure with ambient temperature in
          altering the rate of change of IWL_S with changes in T_a can
          be seen.
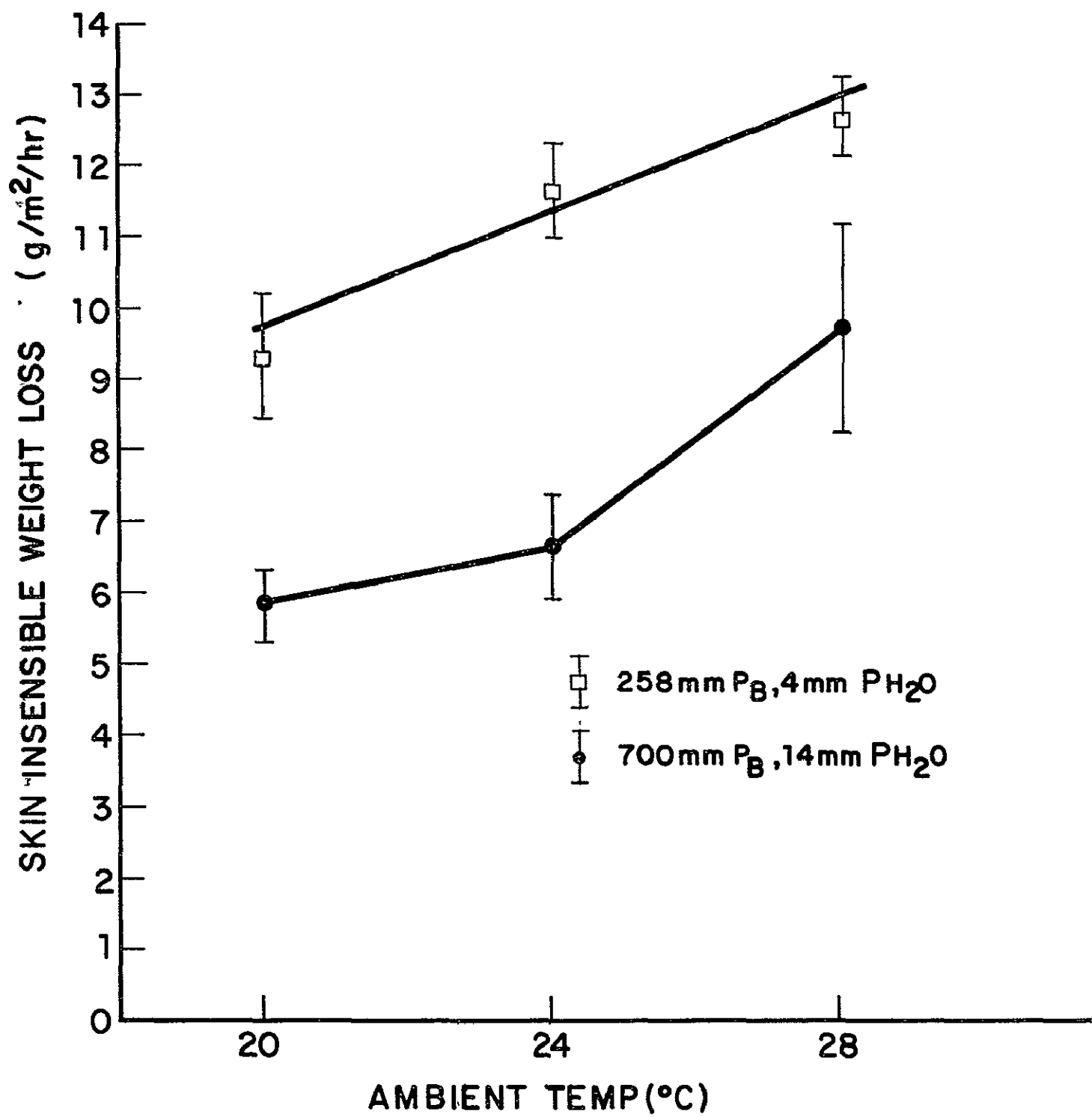
Fig. 11   Interaction of P_B and T_a with P_{H_2O} in determining rates of
skin insensible weight loss. The iso-P_B-T_a weight loss
slopes are nearly parallel except for the 700 mm. P_B-28° C.
T_a line. Under these conditions, thermal sweating was noted
at 14 mm. Hg P_{H_2O} causing a marked shift in the slope. Sig-
nificance levels for the differences in IWL_S rates with
varying ambient conditions are shown.
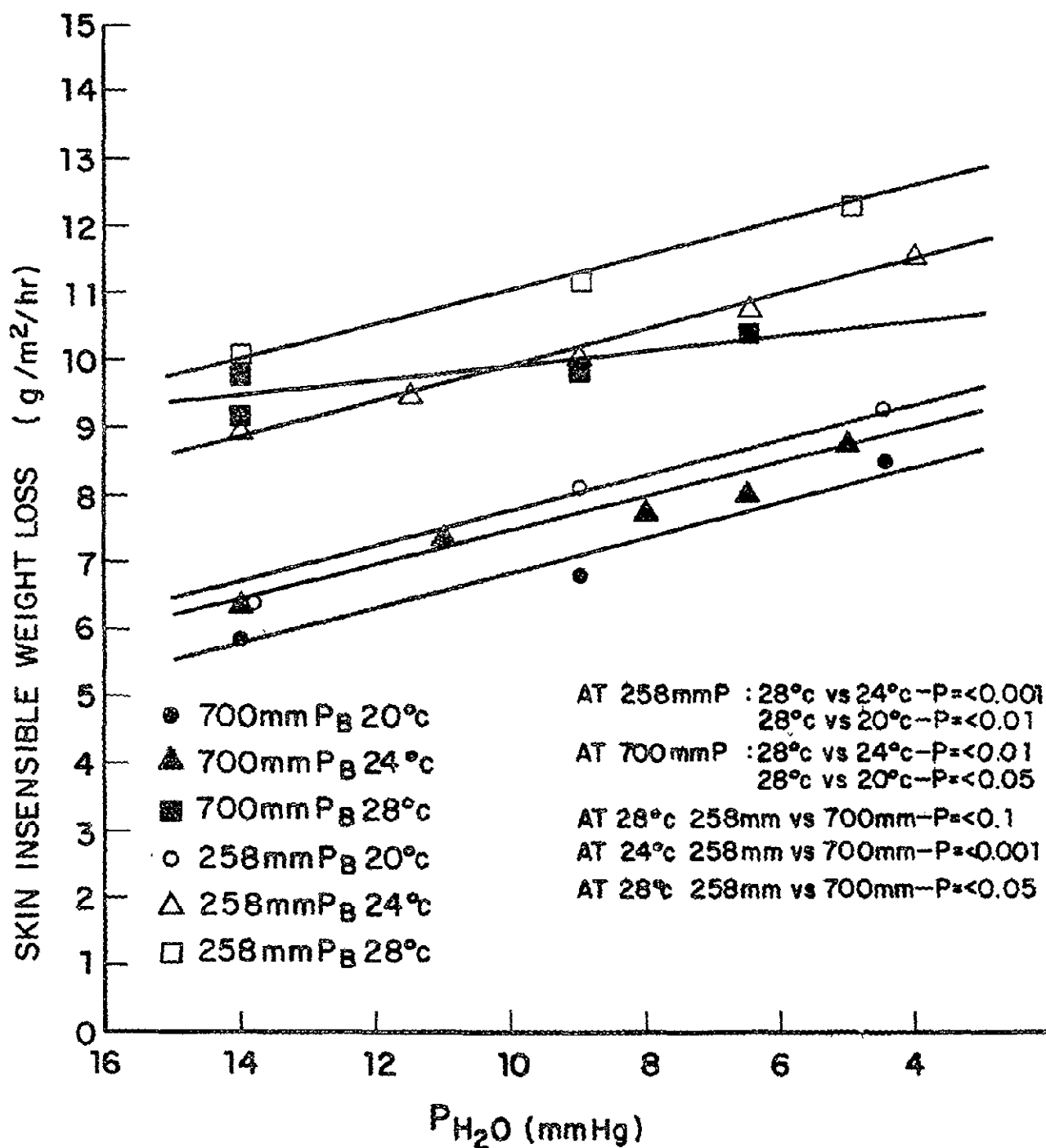
Fig. 12 Relationship of wind velocity (V) to rate of skin insensible weight at 28° C. T_a and varying P_B and P_{H_2O}. V is expressed in both ft./min. and m./min. In the region of free convective cooling, the differences among the four values of IWL_s are significant to the .05 level. In the region of forced convective cooling, however, the value differences lose all significance.
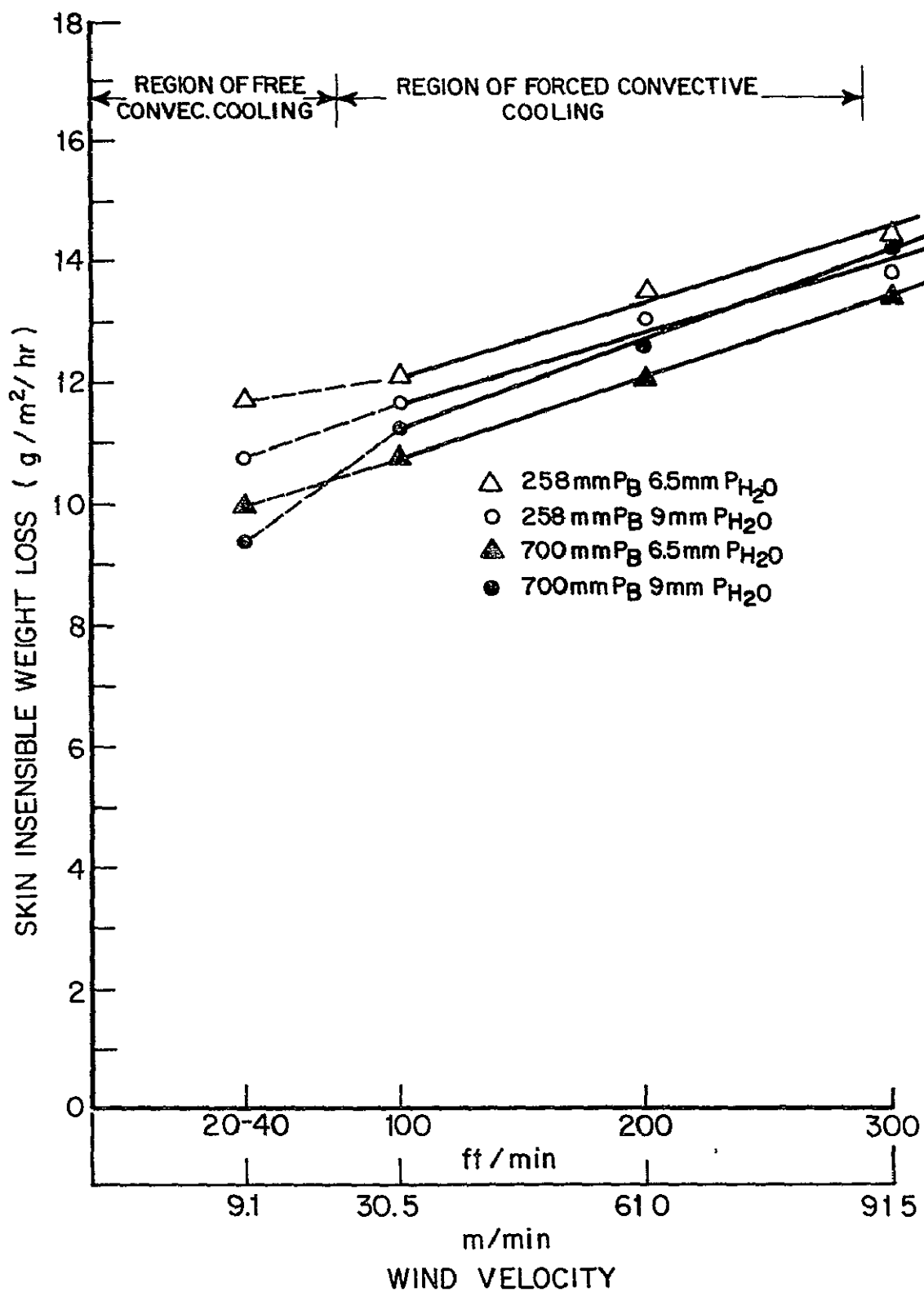
Fig. 13   Effects of increases in four environmental variables upon
           alterations in the rate of skin insensible weight loss.
           (The rates of change of IWL_S are expressed in terms of units
           of environmental change.)
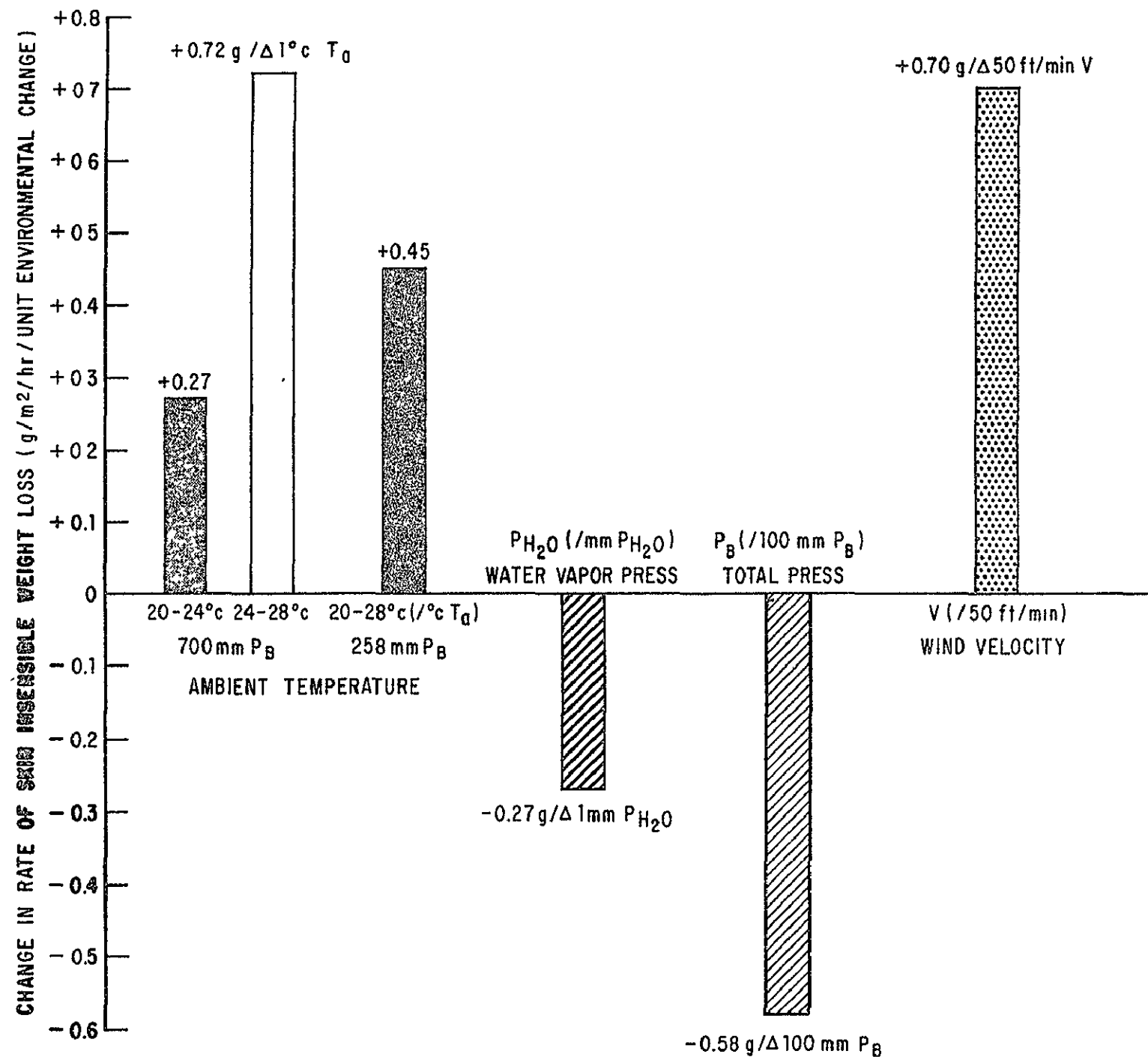
Fig. 14   Relationship of average skin temperature (T_s) to T_a for varying combinations of P_B, G.C., and V. Note that T_s is consistently higher for a given T_a when the total pressure is reduced.

-175-
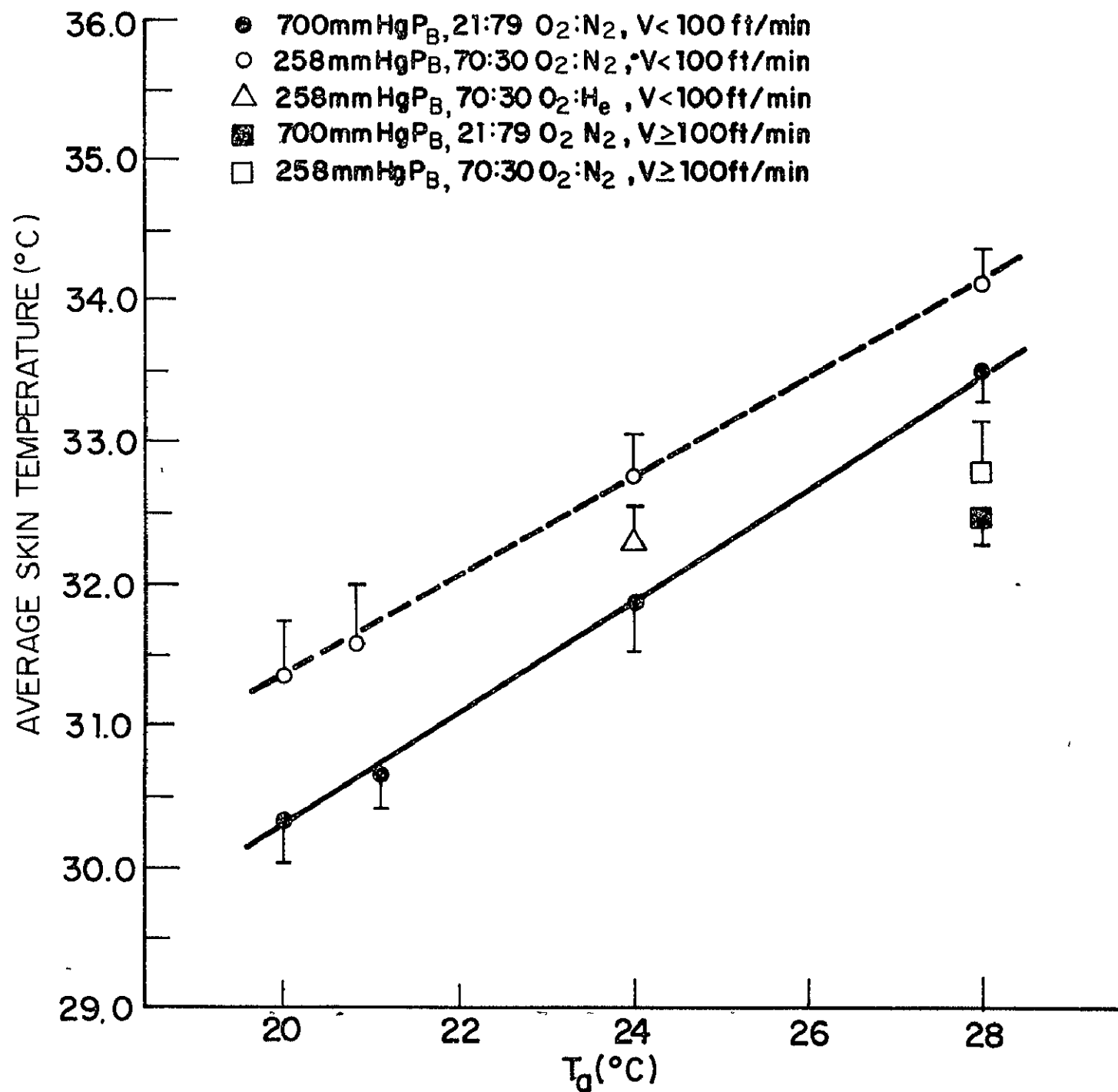
Fig. 15   Relationship of average skin temperature (T_s) to skin insen
sible weight loss. A clear trend but a wide scatter is
present. Note the marked effect of elevated wind velocitie·
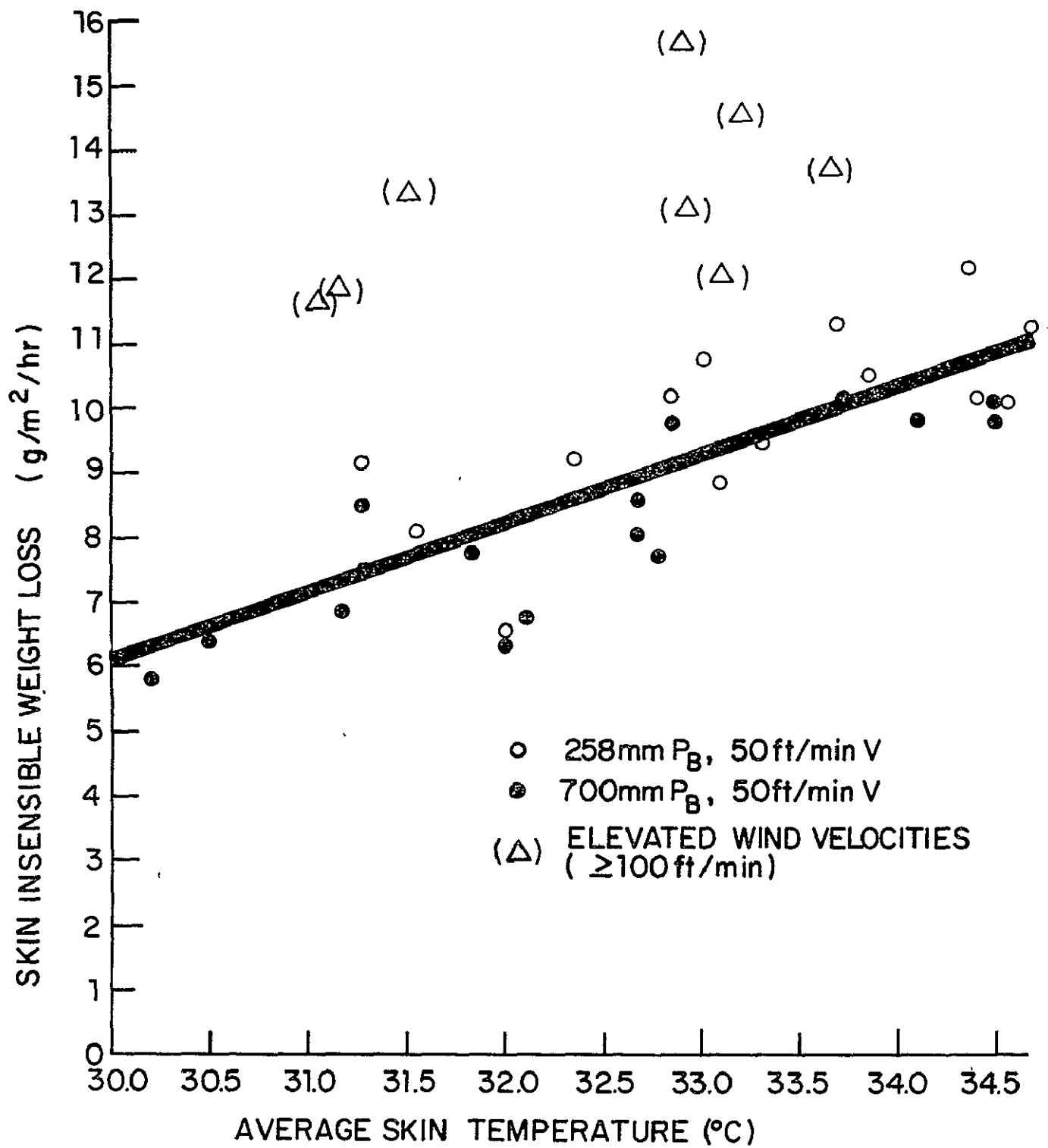
Fig. 16 Intake and output of six subjects during seven consecutive
experiments at 700 mm. Hg P_B. Grand total output includes
all sources of weight loss except IWL_G.

Legend:
- TOTAL INTAKE (W_i)
- GRAND TOTAL OUTPUT $(W_o + W_{e_1})$

Y-axis: g/24 HRS, values 0, 500, 1000, 1500, 2000, 2500, 3000

X-axis: EXP. 1, 2, 3, 4, 5, 6, 7, MEAN (each with I and O)
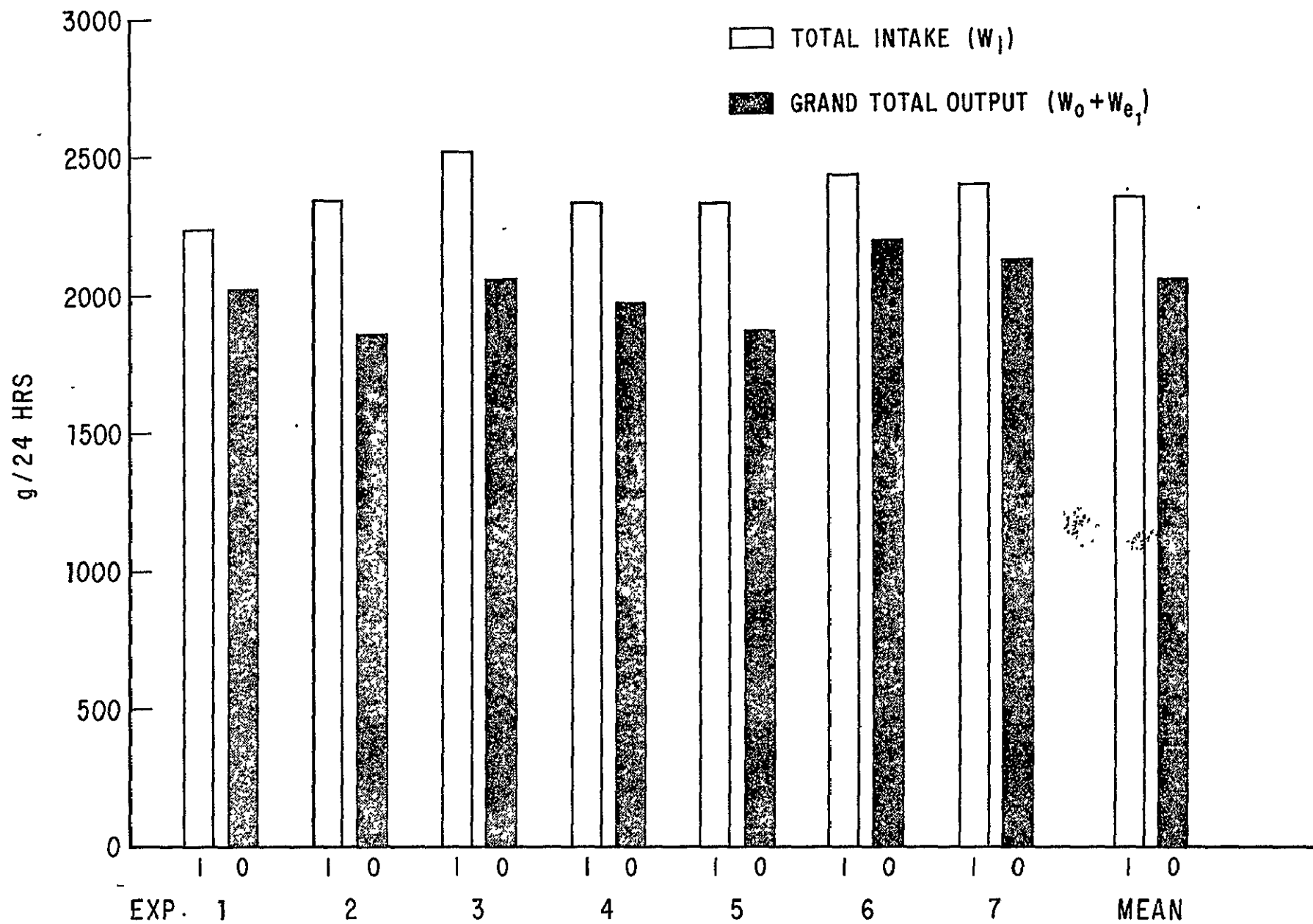
Fig. 17   Effect of total barometric pressure (P_B) upon weight balance and fluid loss (paired 48-hr and 24-hr experiments). Significance levels are shown.

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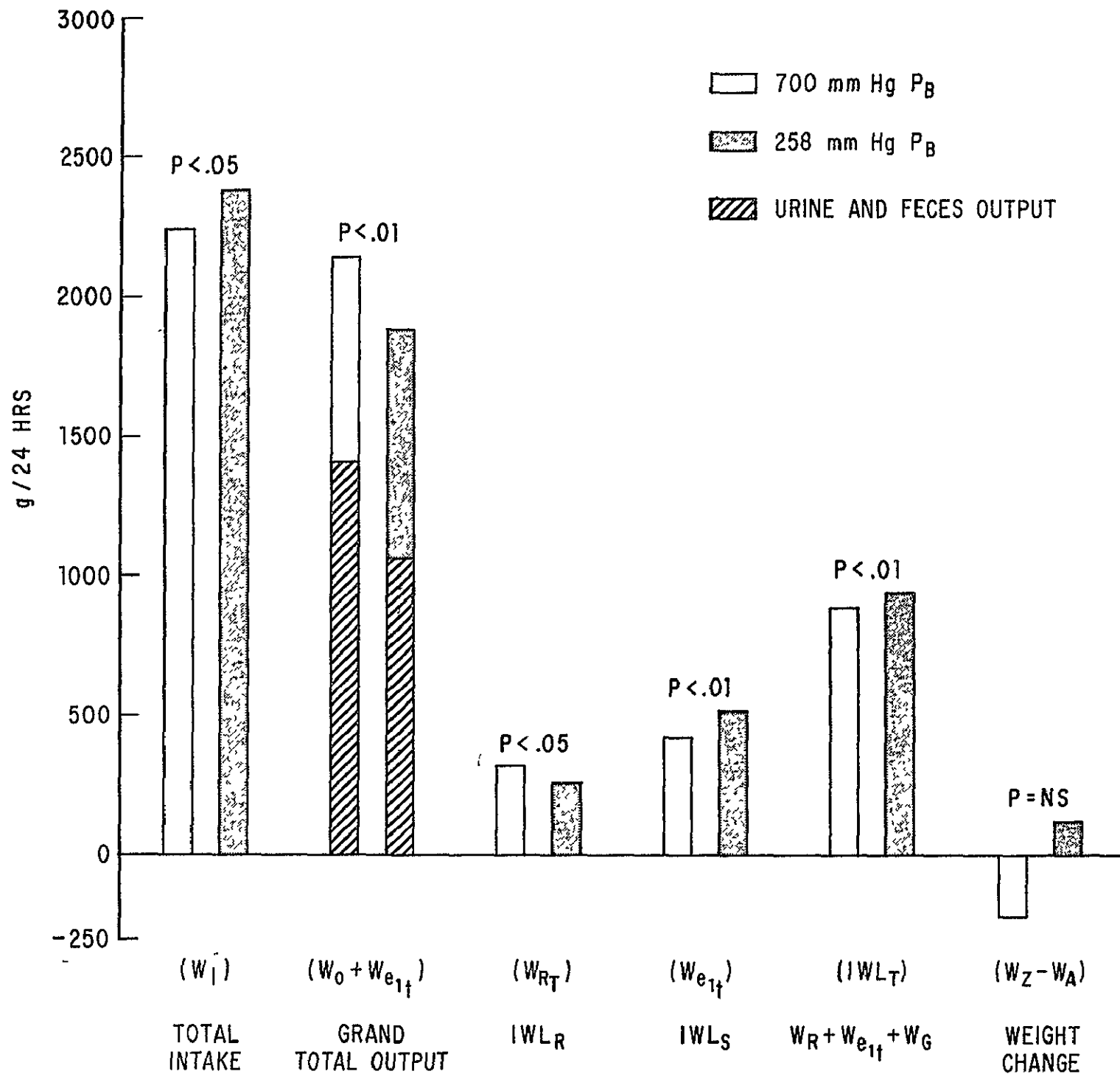
Fig. 18   Effect of water vapor pressure (P_{H_2O}) upon weight balance
and fluid loss (paired 48-hr and 24-hr experiments). Sig-
nificance levels are shown.
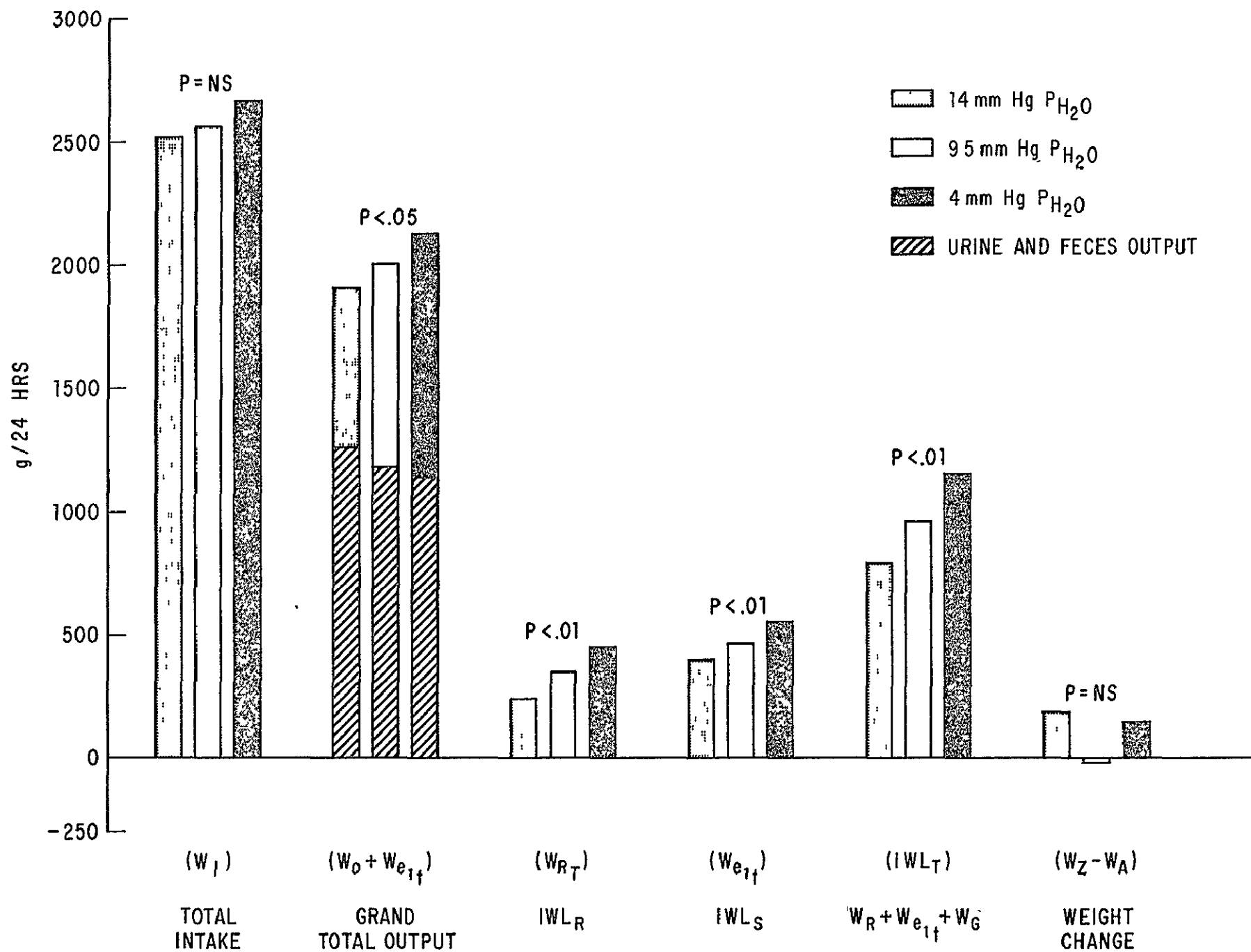
Fig. 19   Effect of ambient temperature (T_a) upon weight balance and
fluid loss (paired 48-hr and 24-hr experiments). Signifi-
cance levels are shown.

- $-LLI-$
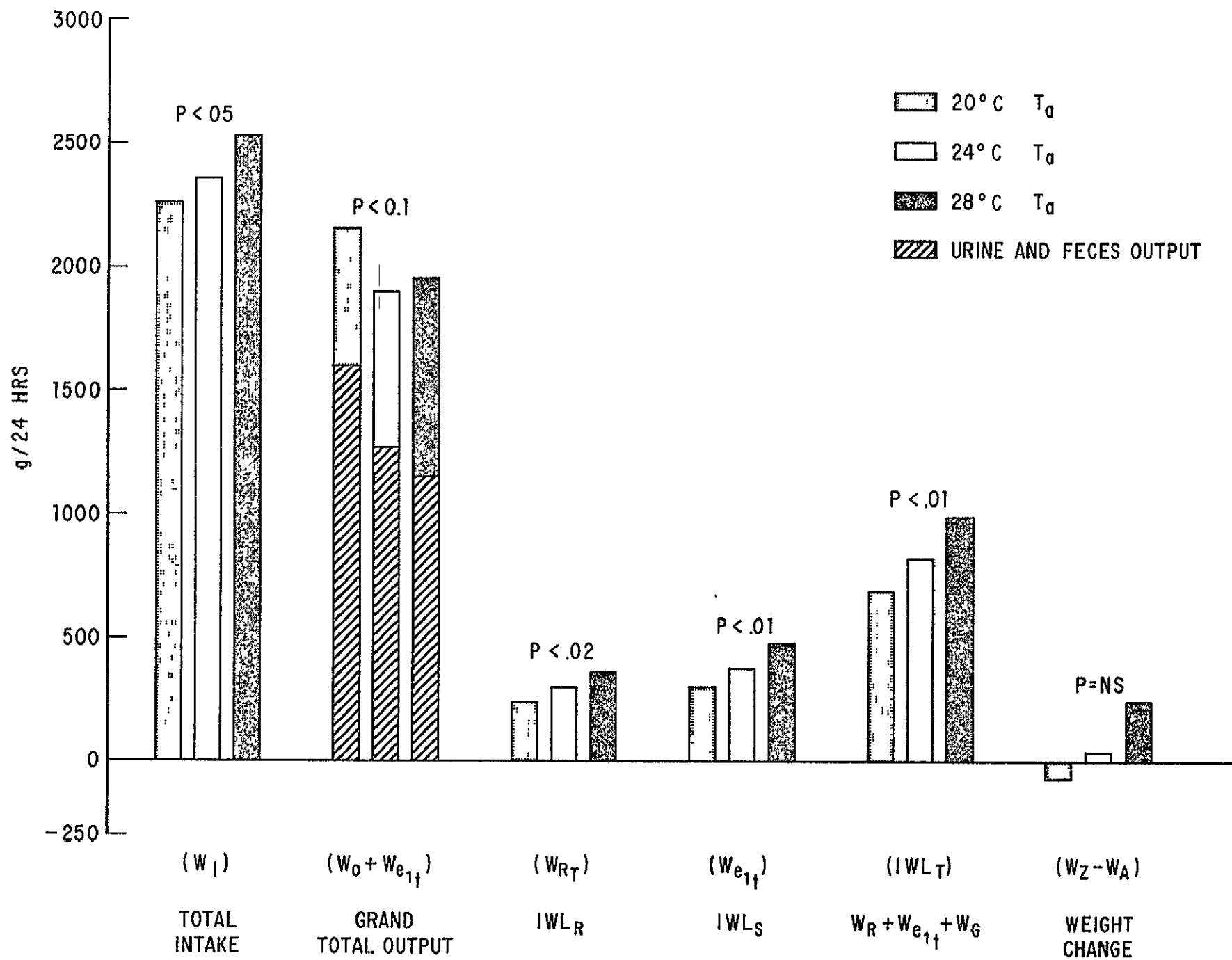
Fig. 20   Effect of gas composition (G.C.) on weight balance and
          fluid loss at 258 mm. Hg P_B (paired experiments). Signifi-
          cance levels are shown.
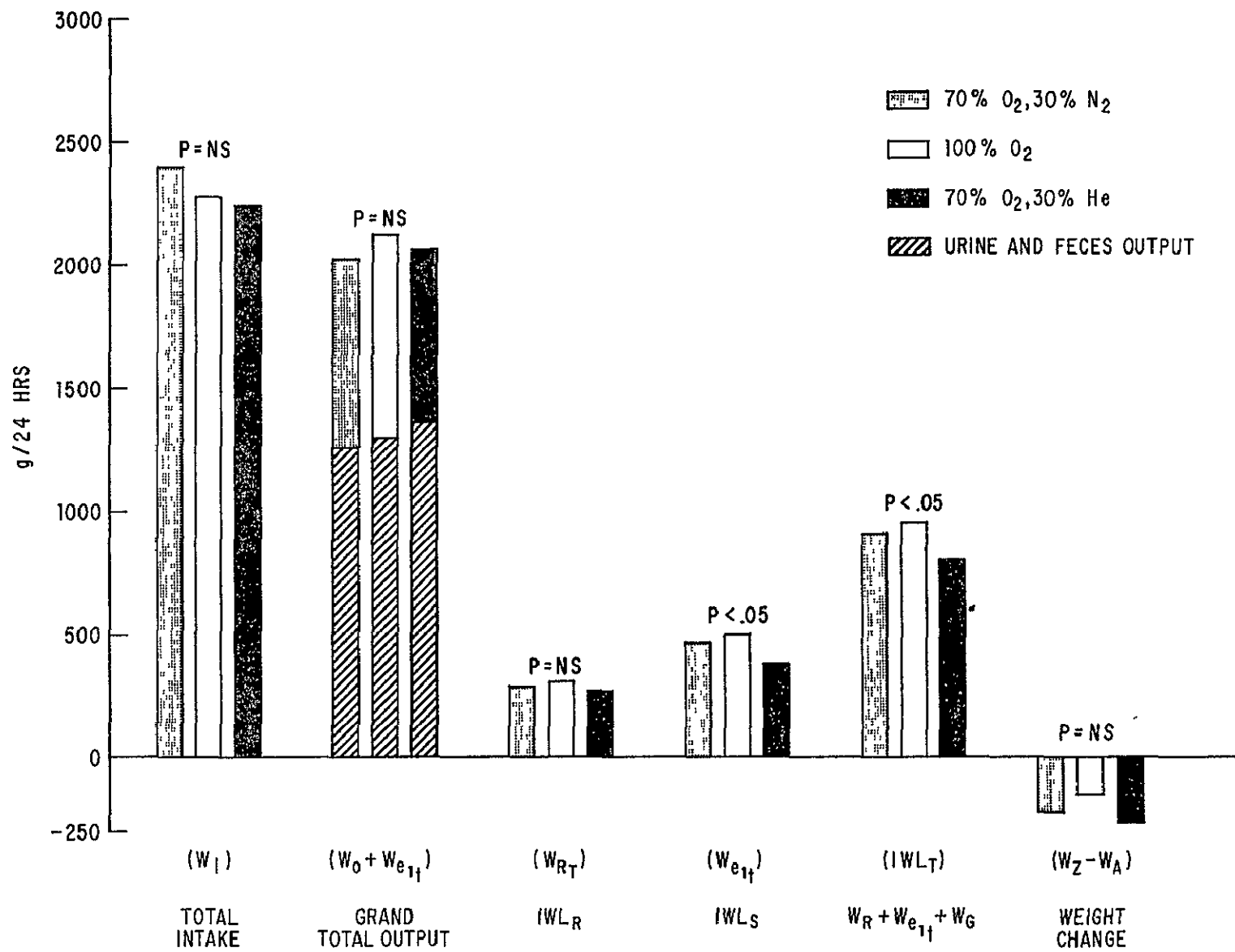
Fig. 21   Direct and indirect measurement of skin insensible weight loss (W_{e1_t} and W_{e2_t}); relationship to P_{H_2O}, P_B, and y.
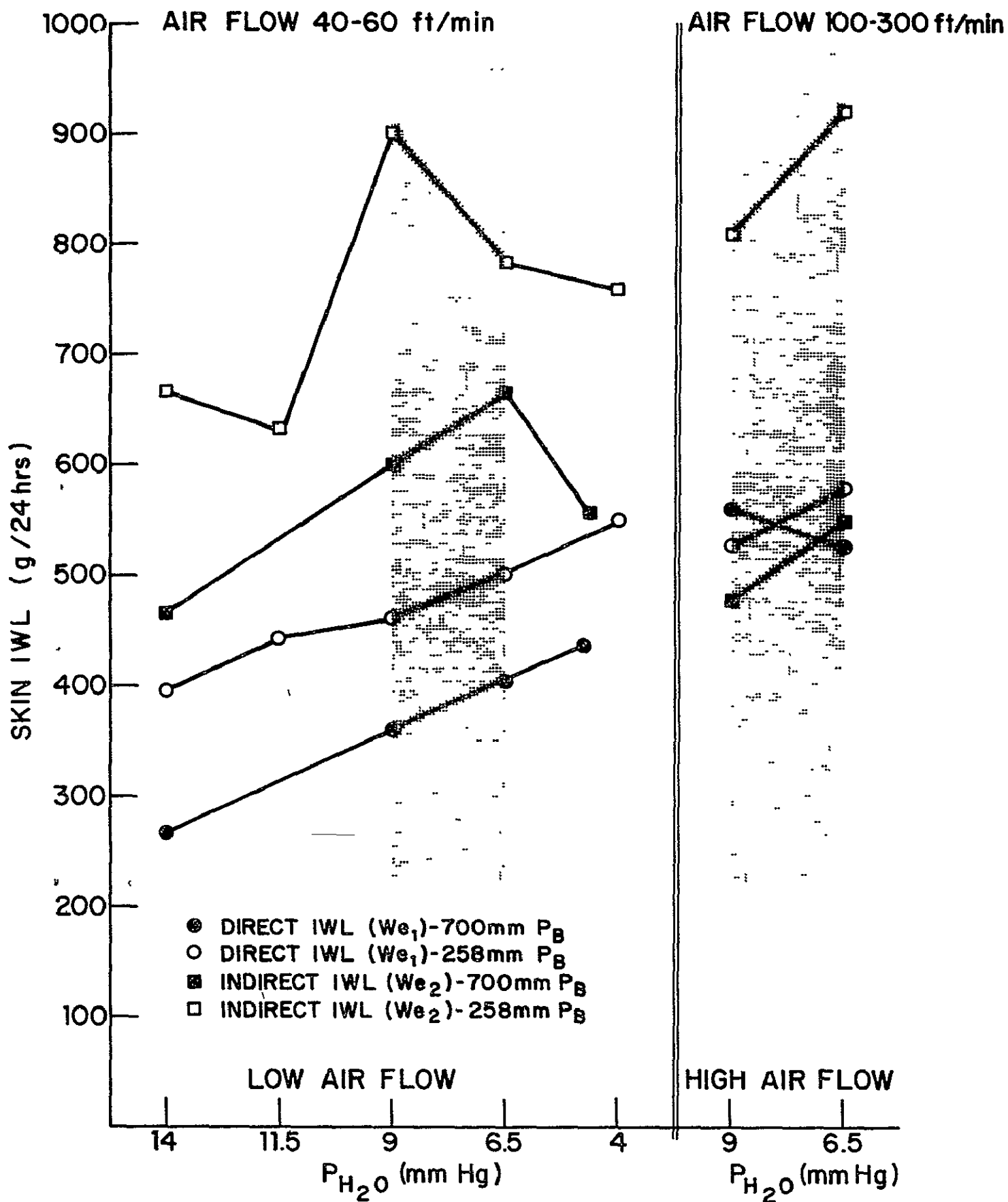
Fig. 22 Direct and indirect measurement of skin insensible weight
loss (W_{e1_t} and W_{e2_t}); relationship to T_a and P_B.

INDIRECT IWL (W_{e_2}) 700mm P_B

DIRECT IWL (W_{e_1}) 258mm P_B

DIRECT IWL (W_{e_1}) 700mm P_B

SKIN IWL (g/24 hrs)

T_a (°C)
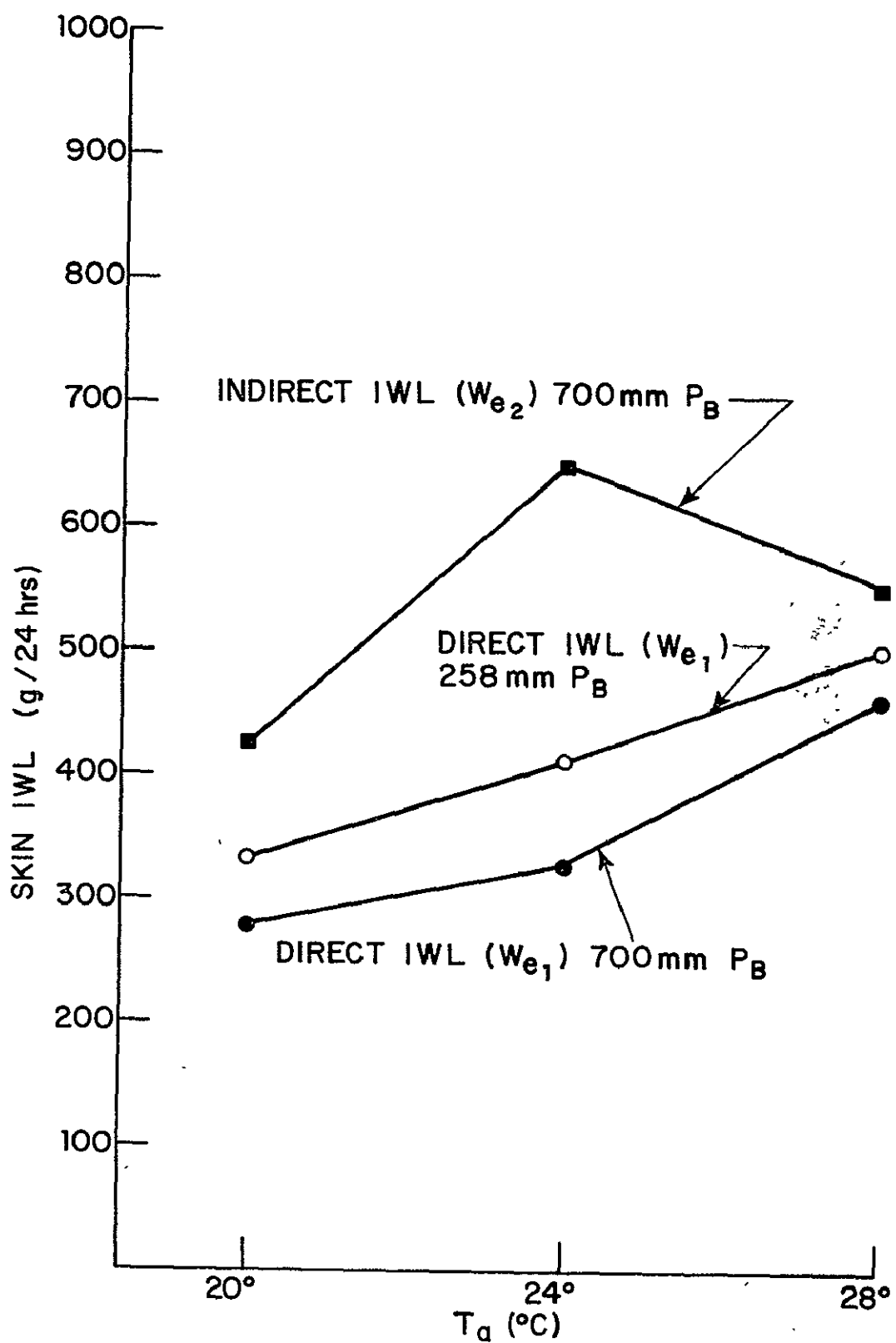
Fig. 23   Relationship of respiratory-insensible water loss (W_R) to P_{H_2O}, R.H., and P_B at 24° C. T_a. Mean values and S.D. are shown.
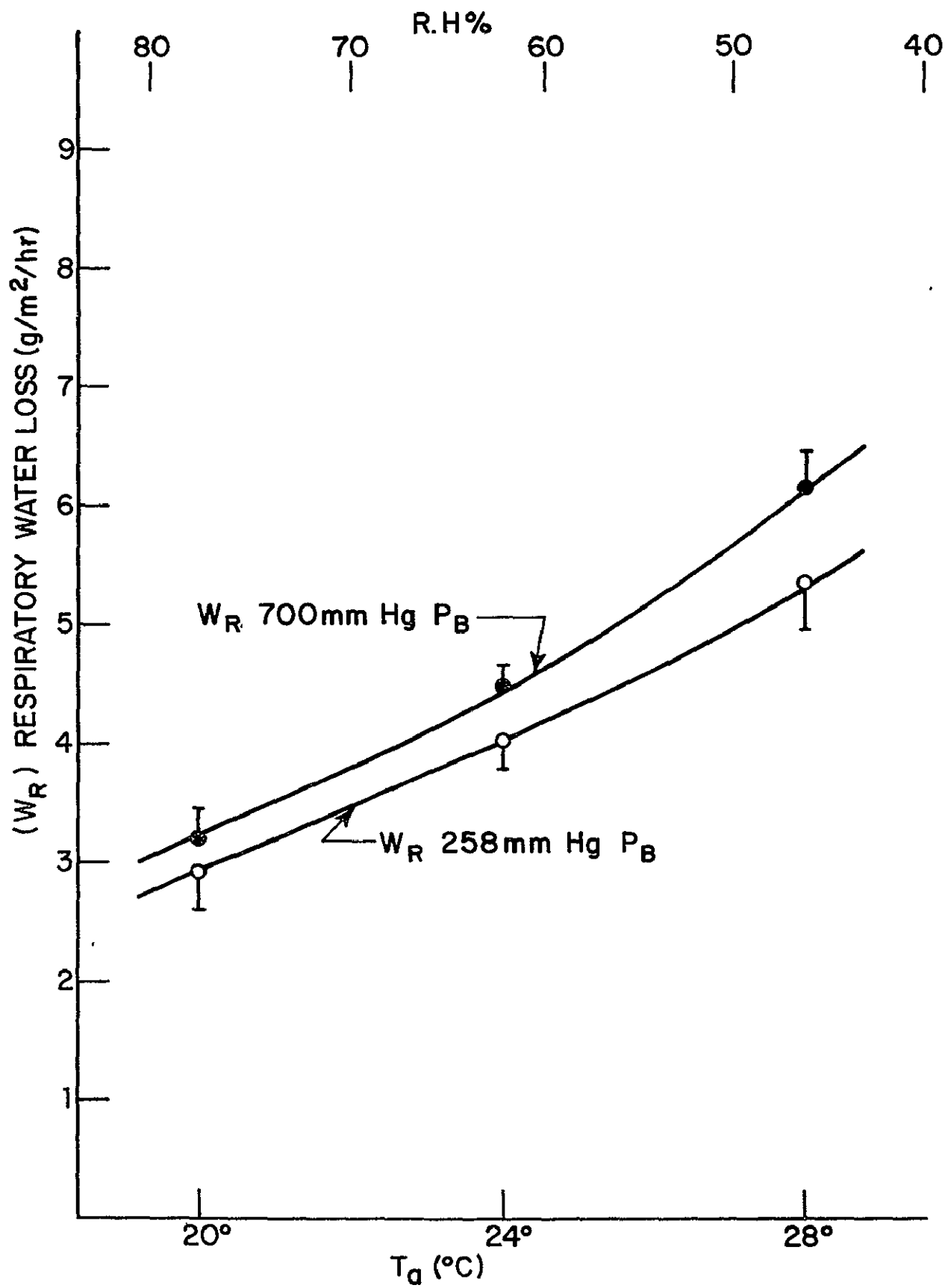
Fig. 24   Relationship of respiratory insensible water loss (W_R) to
T_a, P_B, and R.H. at 14 mm. Hg P_{H2O}. Mean values and S.D.
are shown.
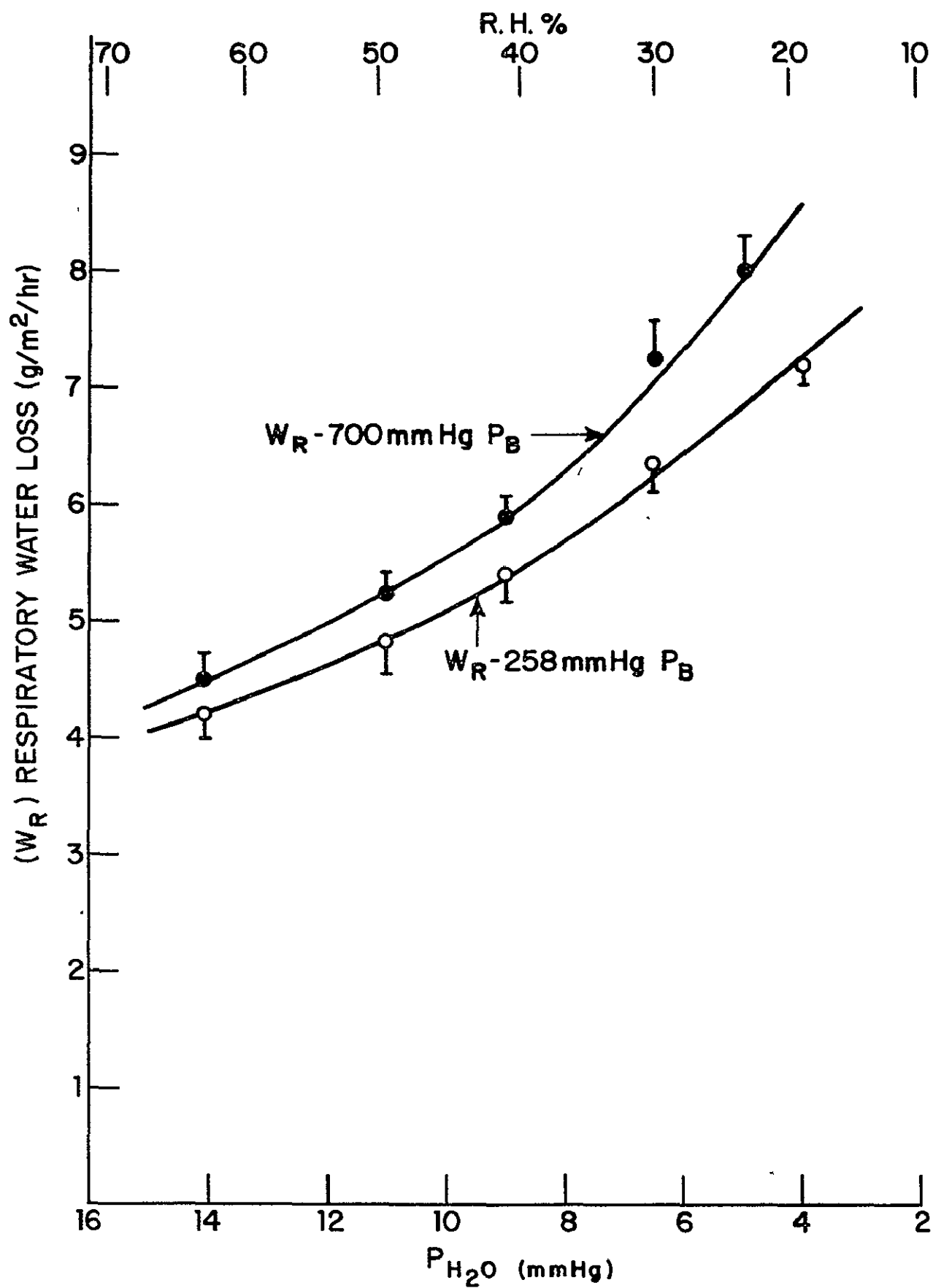
Fig. 25   Relationship of relative humidity of inspired air to rates
           of respiratory insensible water loss (W_R) at two levels of
           P_B.   The data represent multiple values of T_a and P_{H_2O}.
           Average pulmonary ventilation rates for the two levels of
           P_B are shown.
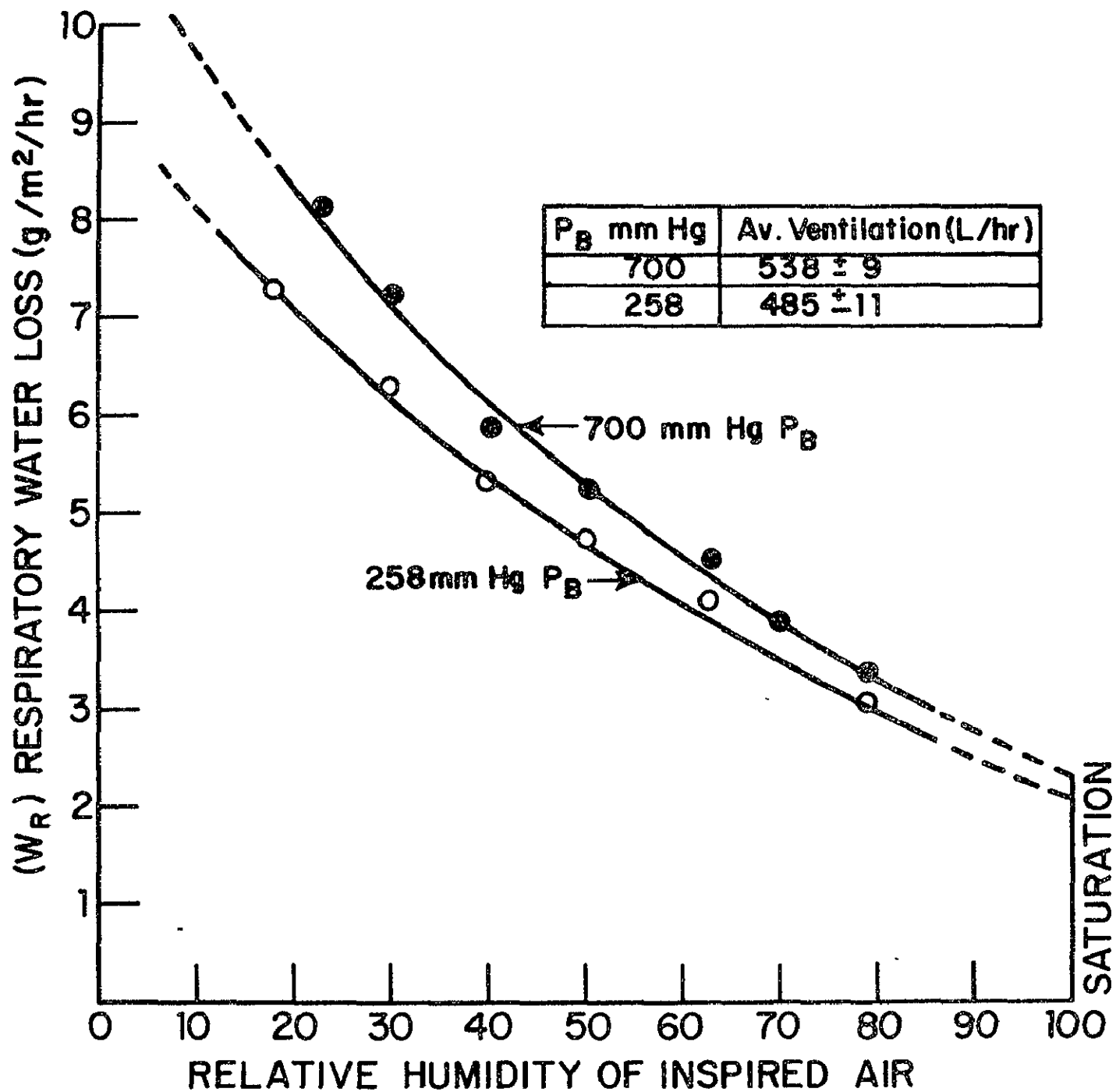
Fig. 26   Relationship of relative humidity of ambient air to rates of skin insensible weight loss (W_{e1}) at two levels of P_B. Note the significant influence of T_a irrespective of its role in the determination of R.H.
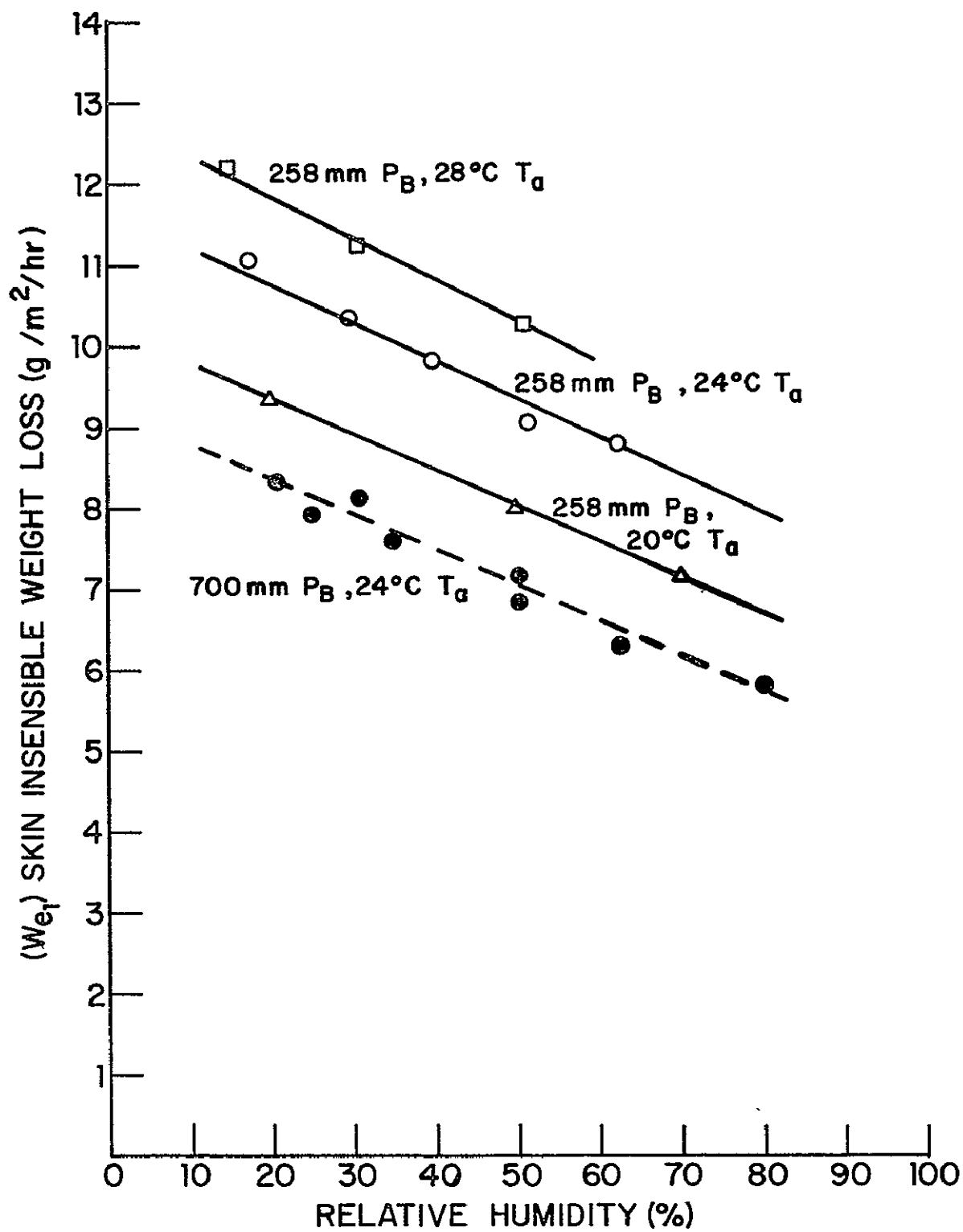
Fig. 27   Total insensible weight loss (IWL_T) and its components,
relationship to P_B and P_{H_2O} at 24° C. T_a.

$IWL_T = IWL_S + IWL_R + IWL_G$

258 mm Hg P_B

700 mm Hg P_B

IWL_T

IWL_S

IWL_R

IWL_G

IWL (g/m²/hr.)

P_{H_2O} (mm Hg)

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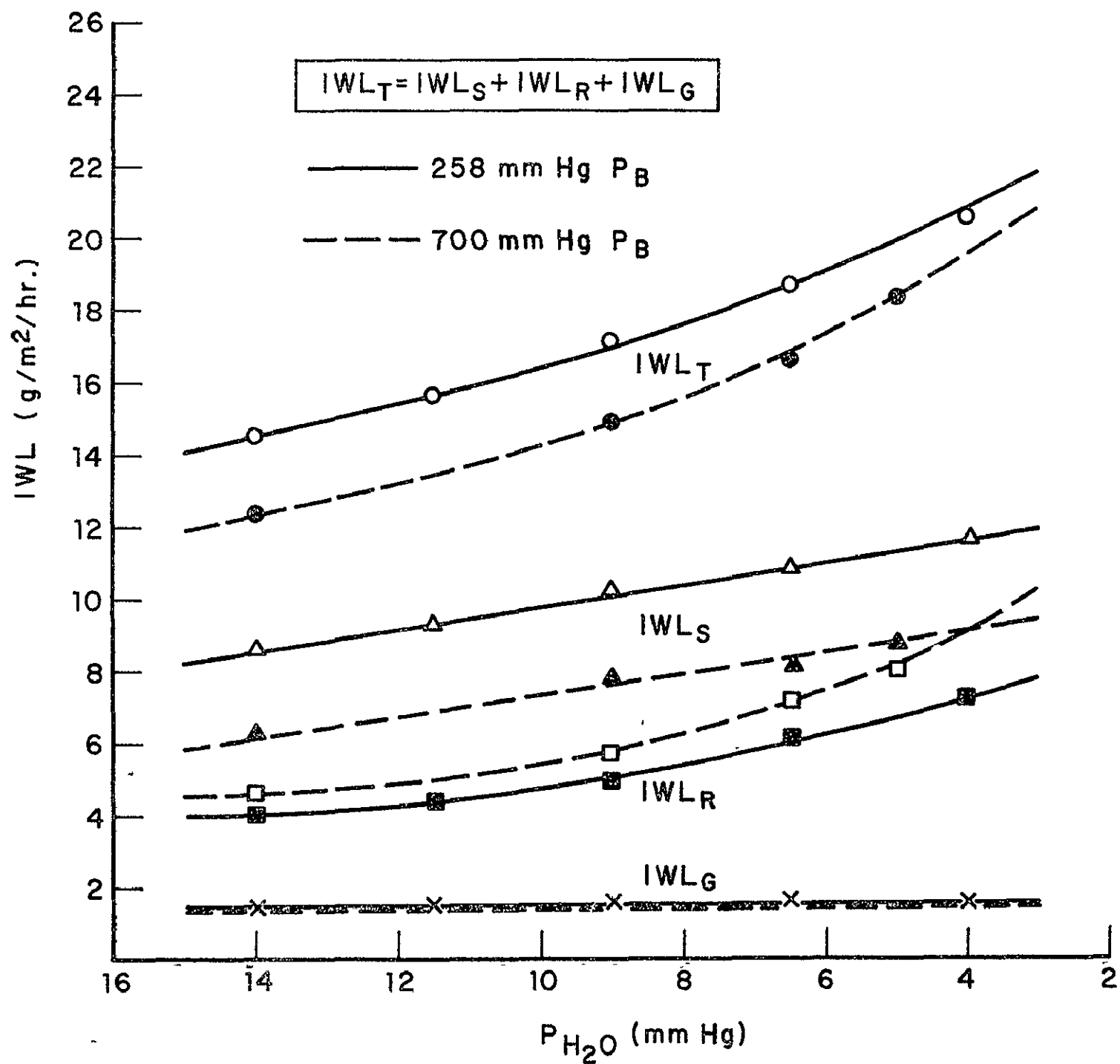
Fig. 28   Total insensible weight loss (IWL$_T$) and its components;
Relationship to T_a and P_B at 14 mm Hg P_B.
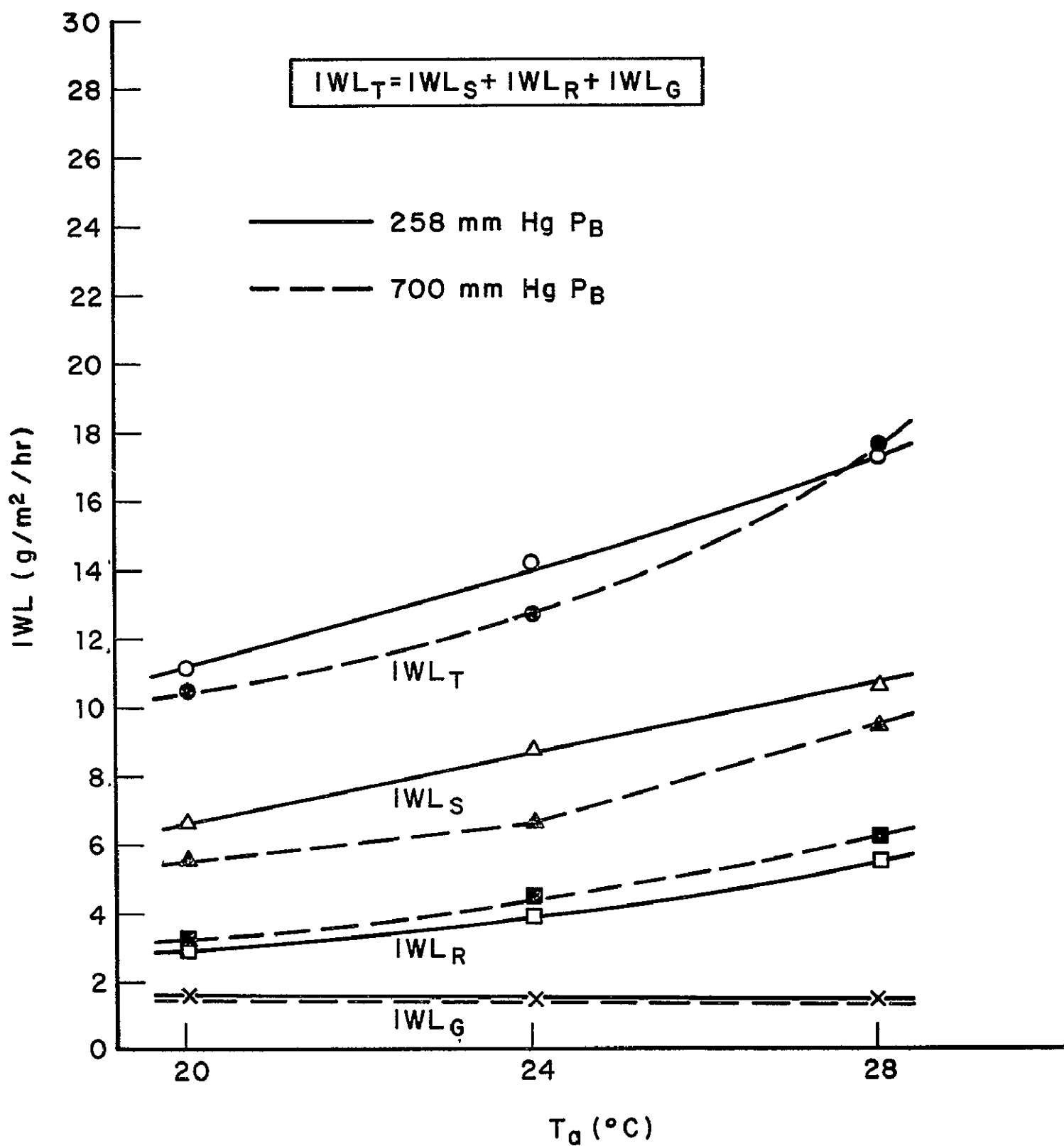
Fig. 29   Components of IWL_T; the varying contributions of IWL_S, IWL_R, and IWL_G. Note that IWL_S is always the most important.

AMBIENT CONDITIONS

258 mm Hg P_B

14 mm Hg P_{H_2O}

20° C T_a

IWL$_G$ 13.6%

IWL$_R$ 25.5%

IWL$_S$ 60.9%

IWL$_G$ 7.3%

IWL$_R$ 39.3%

IWL$_S$ 53.4%
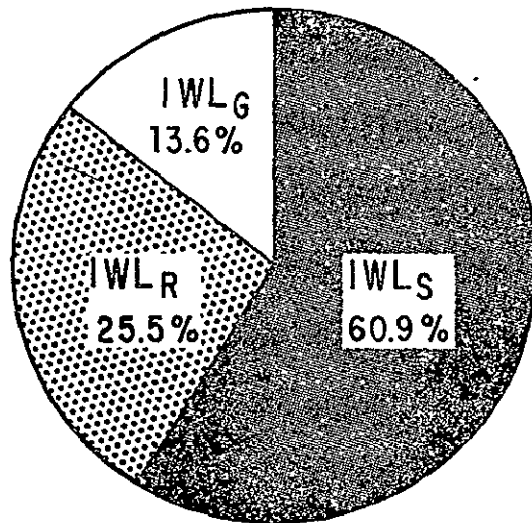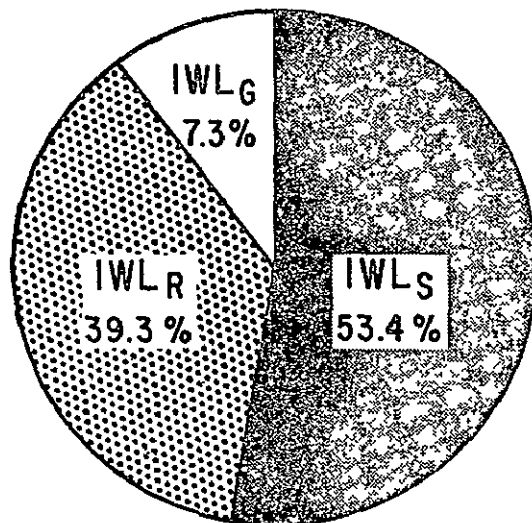
700 mm Hg P_B

9 mm Hg P_{H_2O}

24° C T_a

IWL$_G$ 76%

IWL$_R$ 43.9%

IWL$_S$ 48.5%
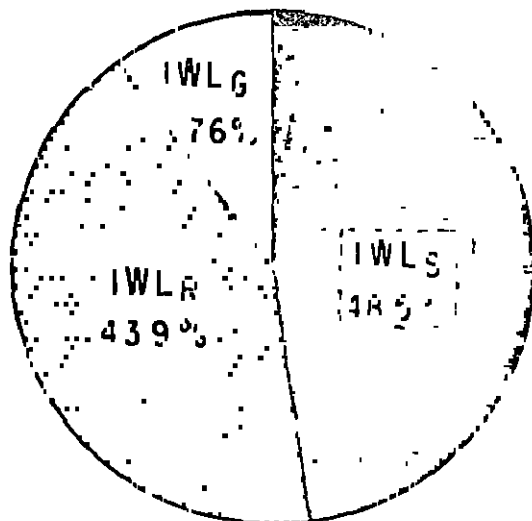
700 mm Hg P_B

5 mm Hg P_{H_2O}

24° C T_a

Fig. 30   Sign and symptom development; relationship to P_{H_2O} and P_B
(all experiments   24-hr duration).

SIGN-SYMPTOM FREQUENCY-SEVERITY INDEX

SYMPTOMS ONLY-700mmHg P_B

SYMPTOMS ONLY-258mmHg P_B

SYMPTOMS ONLY-MEAN P_B

SIGNS + SYMPTOMS-258mmHg P_B

SIGNS + SYMPTOMS-MEAN P_B

SIGNS + SYMPTOMS-700mmHg P

P_{H_2O} (mmHg)
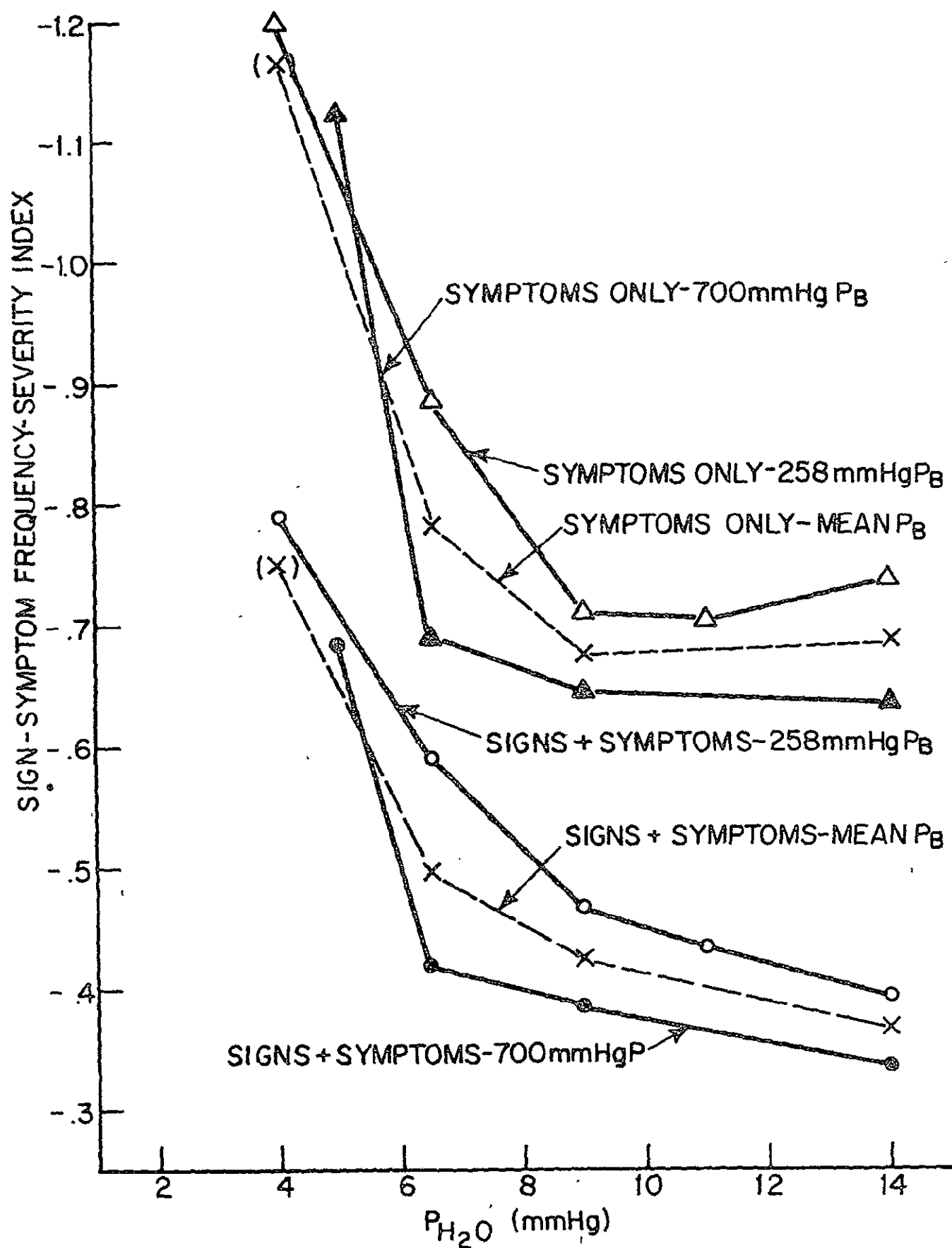
Fig. 31   Sign and symptom development; relationship to $\dot{P}_{H_2O}$ and P_B
(48-hr experiments only).
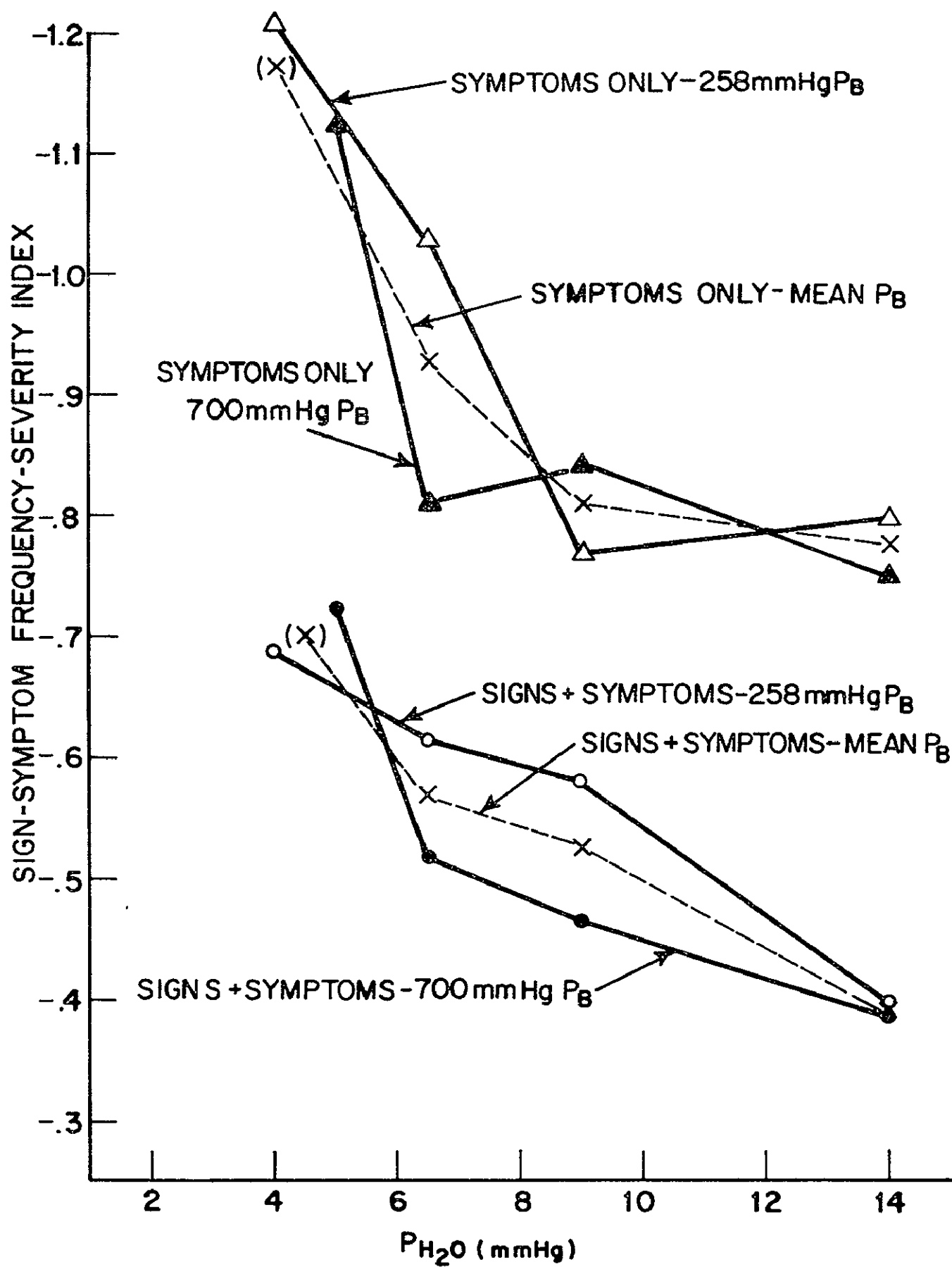
Fig. 32   Sign and symptom development; relationship to T_a and P_B
           (48-hr. experiments only).
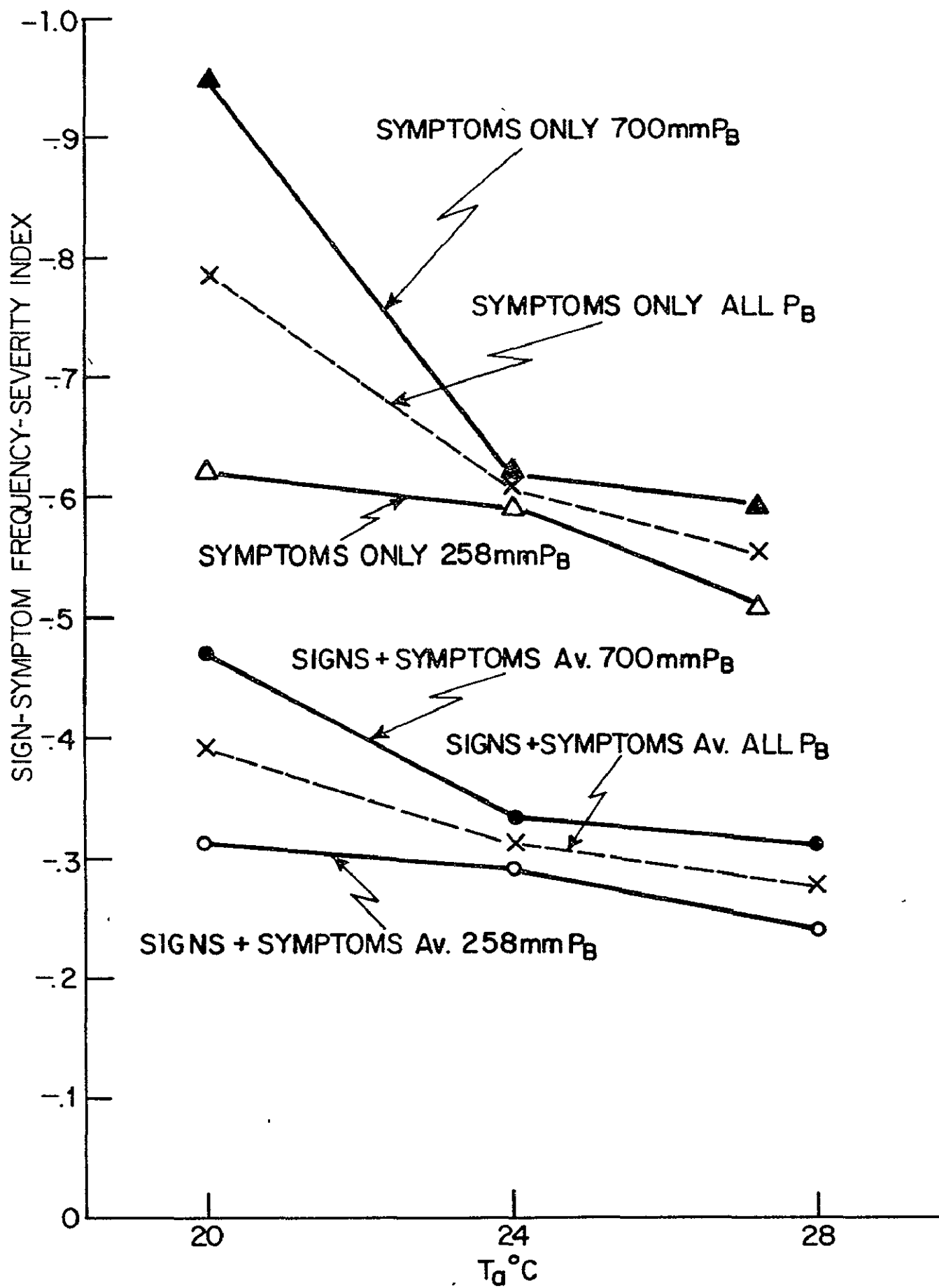
Fig. 33   Time course of symptom development at 4-5 mm and at 14 mm
          Hg. P_{H_2O} (48-hr experiments at 24° C. T_a).   The influence
          of total pressure is also demonstrated.
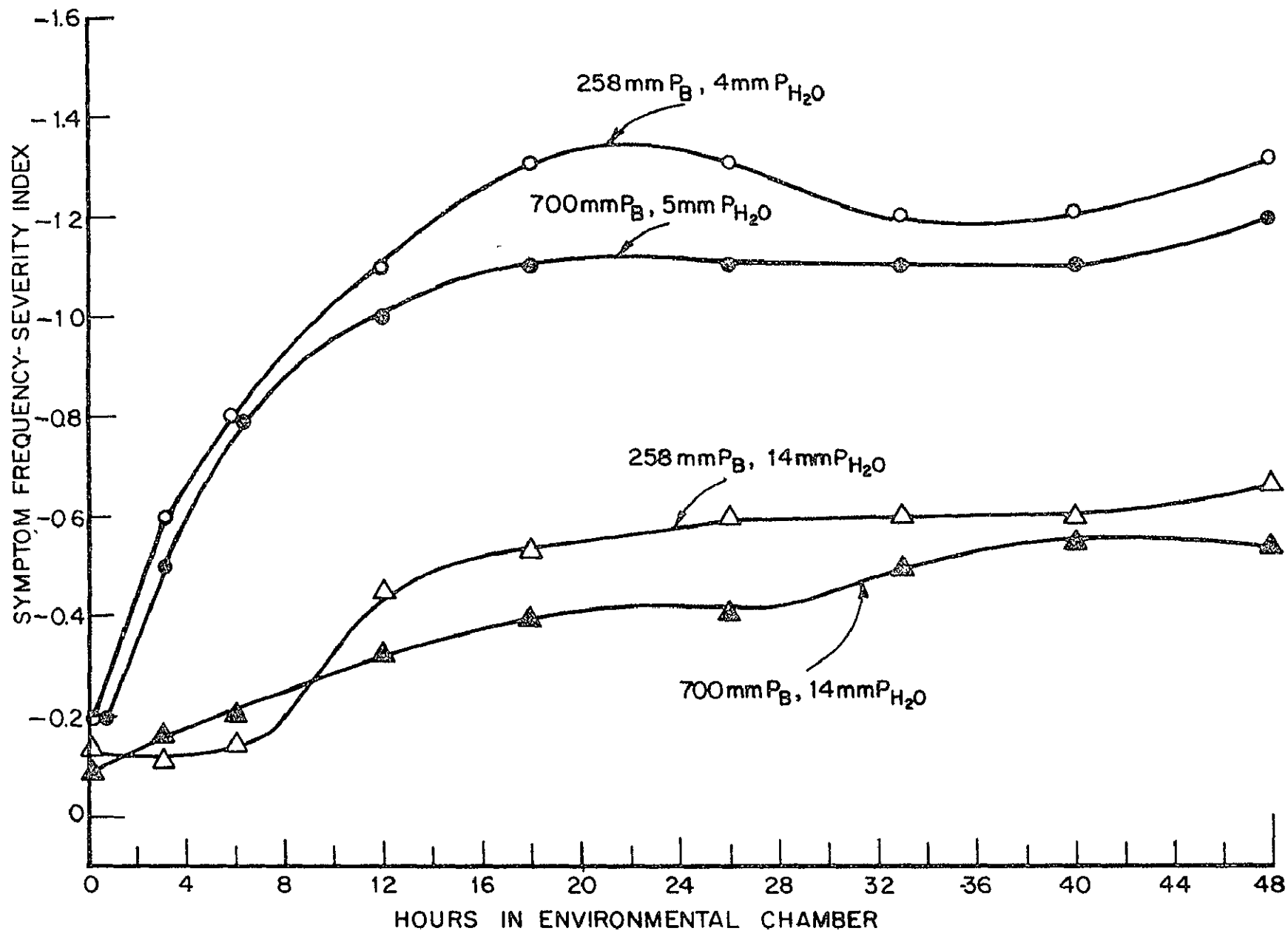
Fig. 34   Time course of symptom development at 6.5 mm and 9 mm Hg
          P_{H2O} (48-hr experiments at 24° C. T_a). The influence of
          P_E is again demonstrated.

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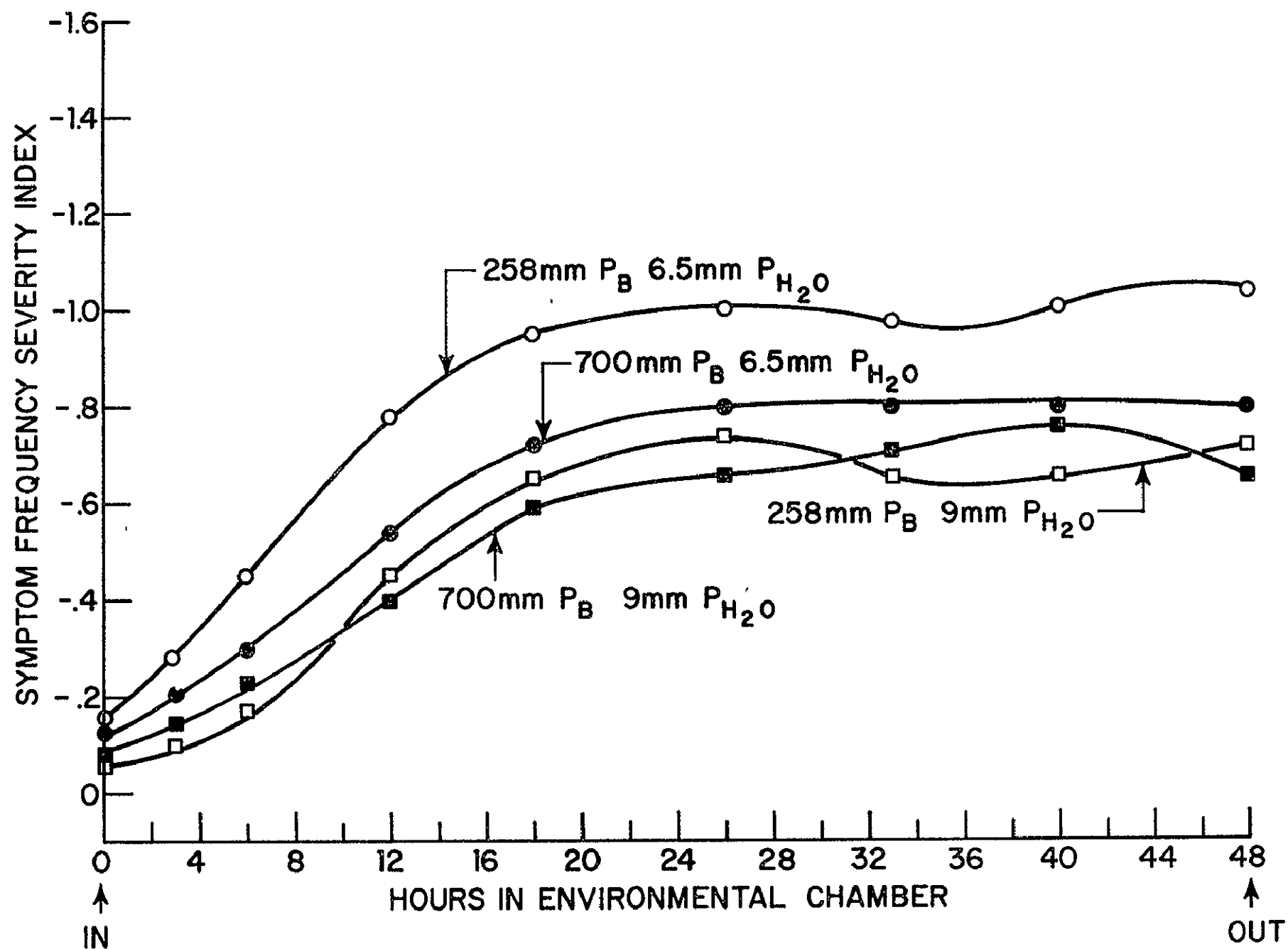
Fig. 35   Time course of sign development at 4-5 mm and 14 mm Hg.
P_{H_2O} (48-hr experiments at 24° C. T_a).   The P_B effect is
also seen.
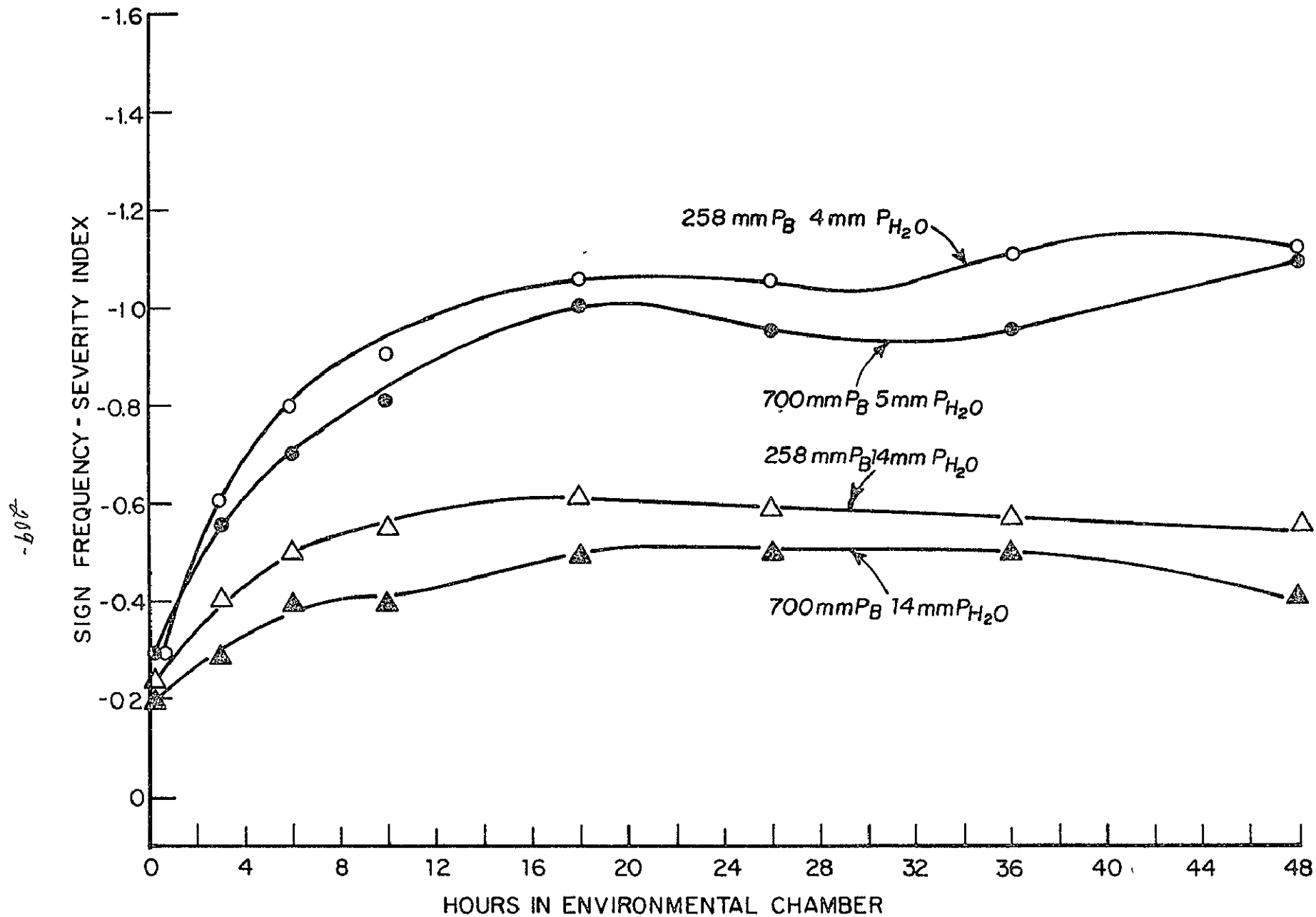
Fig. 36   Time course of sign development at 6.5 mm and 9 mm Hg. P_{H_2O} (48-hr. experiments at 24° C. T_a). The P_B effect is again seen.
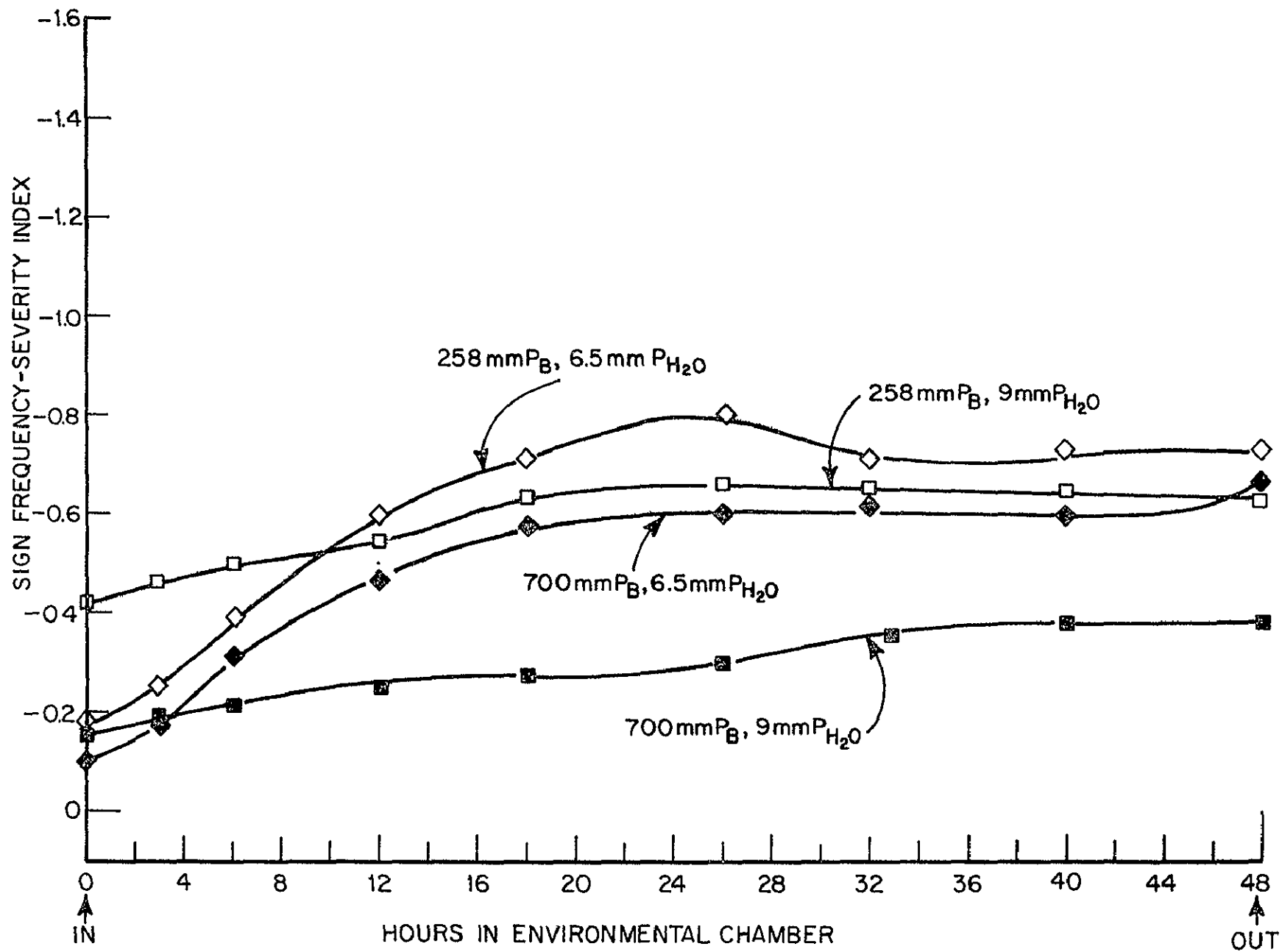
Fig. 37   Frequency-severity of symptoms related to the environment
          by anatomical areas involved, summary of all experiments.

SYMPTOM FREQUENCY – SEVERITY INDEX

NOSE
LIPS
PHARYNX
EYES
MOUTH
TONGUE
SCALP
SKIN
GENERAL MEAN VALUE
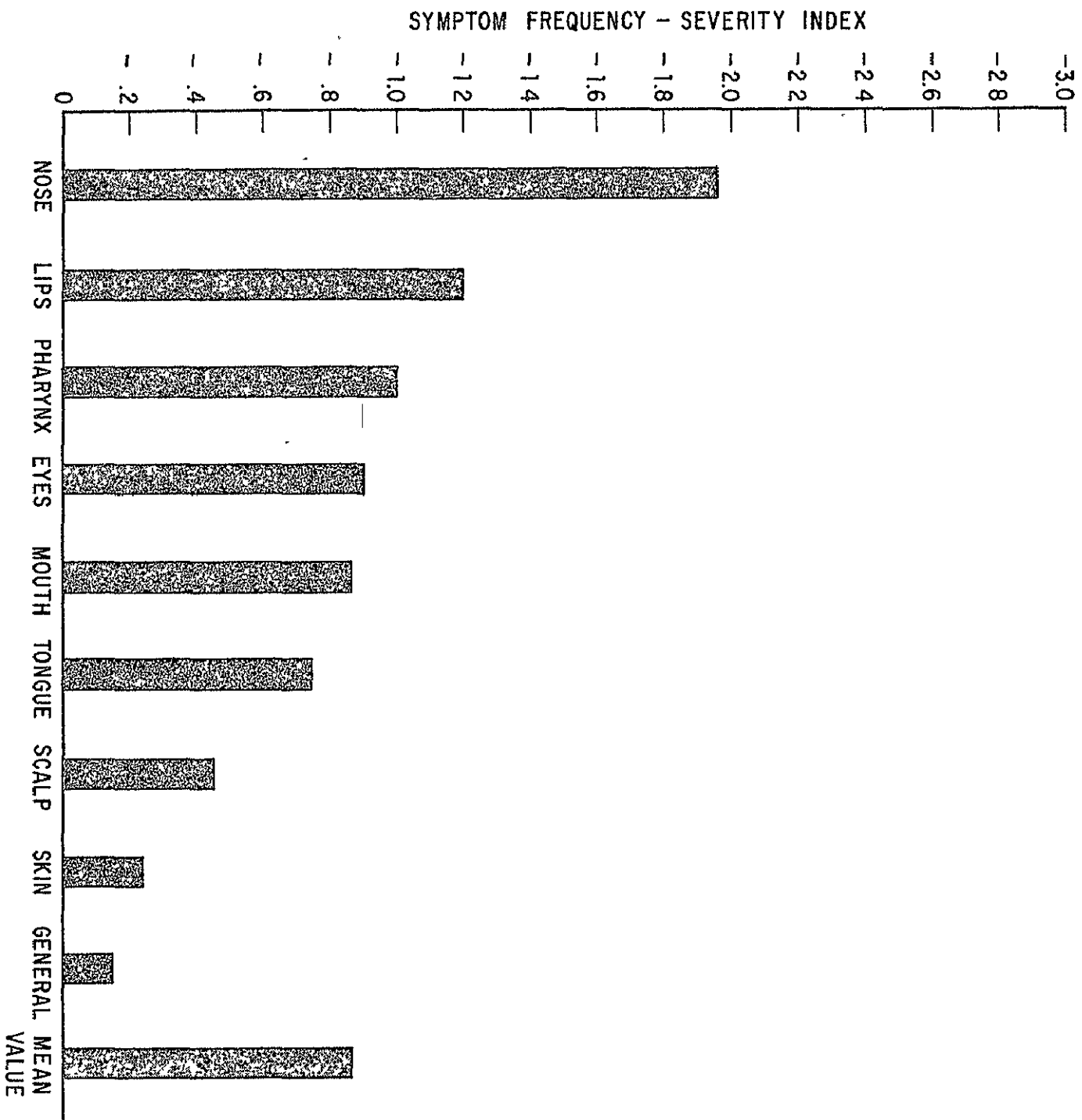
Fig. 38   Frequency-severity of symptoms related to the environment.
Effect of P_B at 24° C. T_a (paired 24-hr and 48-hr experiments)
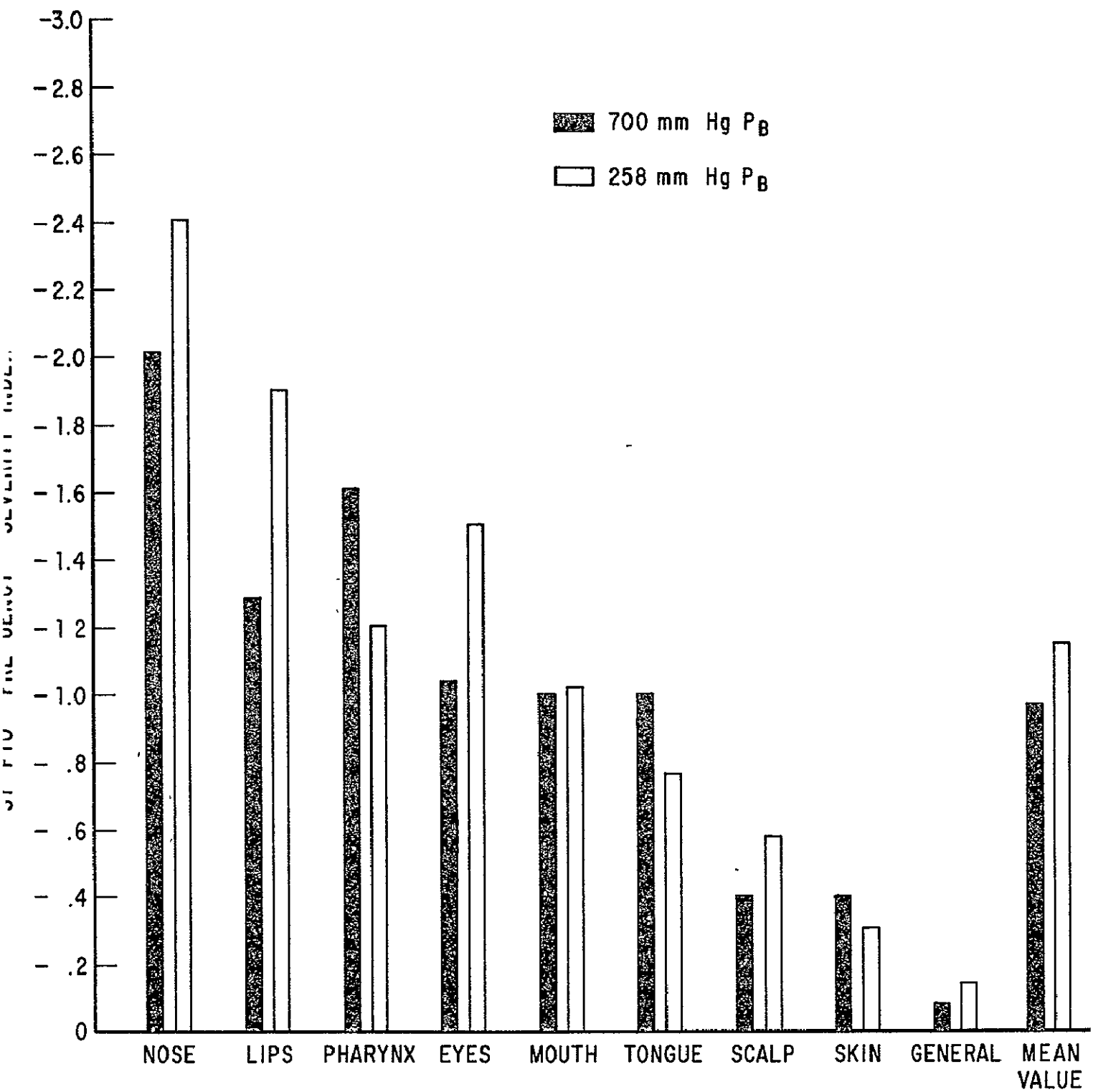
Fig. 39   Frequency-severity of symptoms related to the environment.
Effect of P_{H_2O} at 24° C. T_a (matched 24-hr and 48-hr experiments).
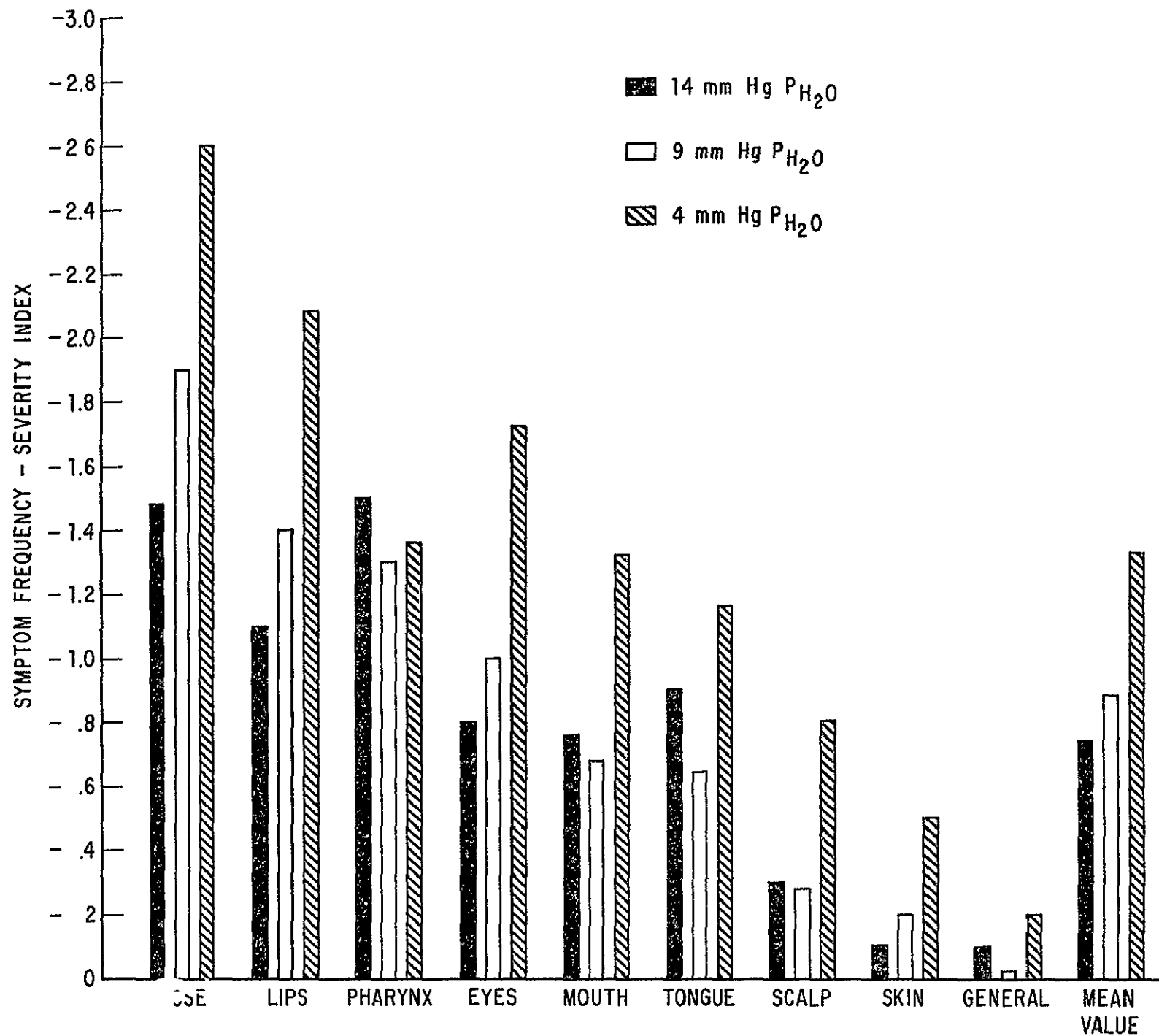
Fig. 40   Frequency-severity of symptoms related to the environment. Effect of T_a at 700 mm Hg P_B (matched 24-hr and 46-hr experiments).
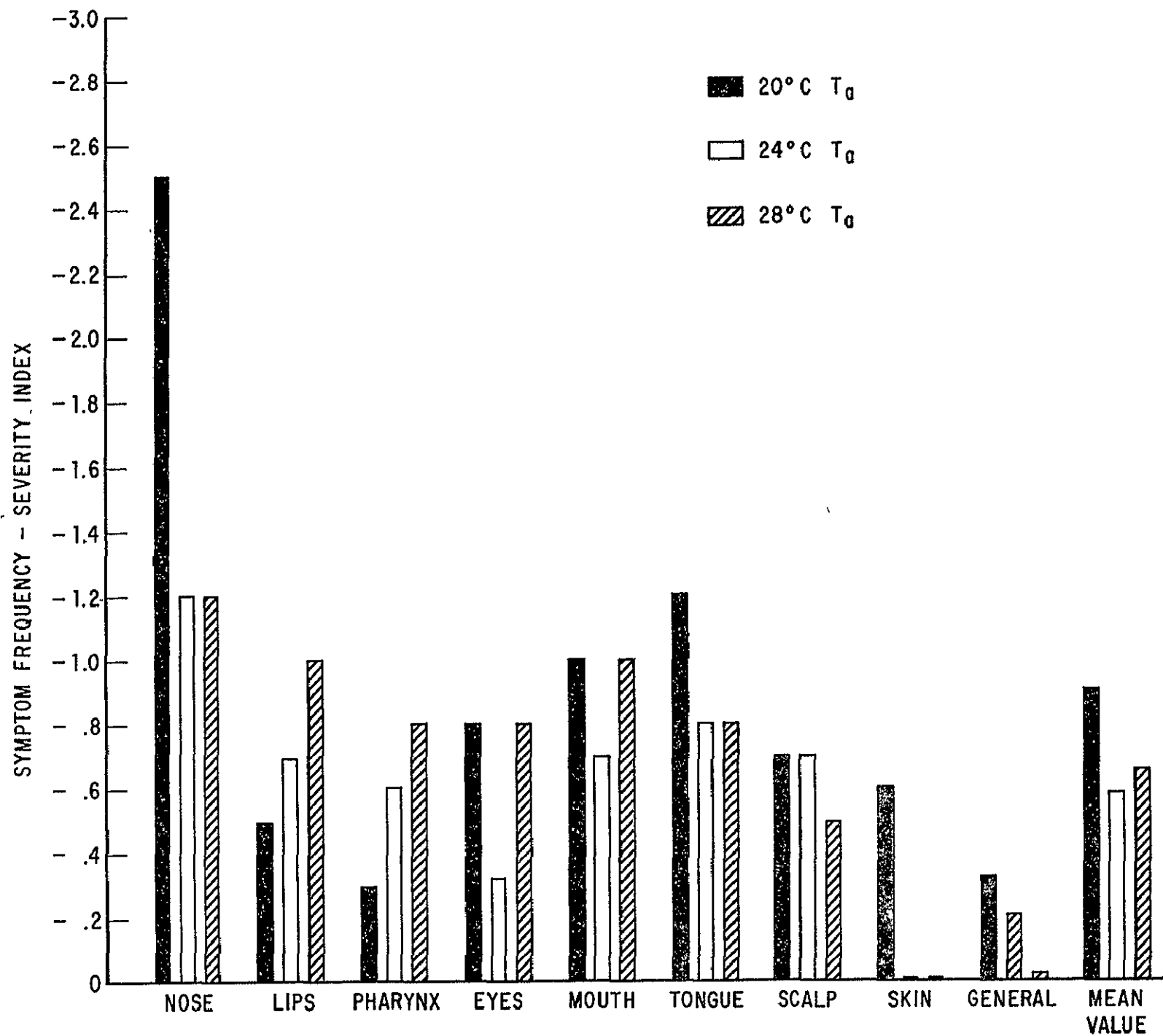
Fig. 41   Frequency-severity of symptoms related to the environment.
           Effect of gas composition at 258 mm Hg P_B, 24° C. T_a
           (matched 24-hr and 48-hr experiments).
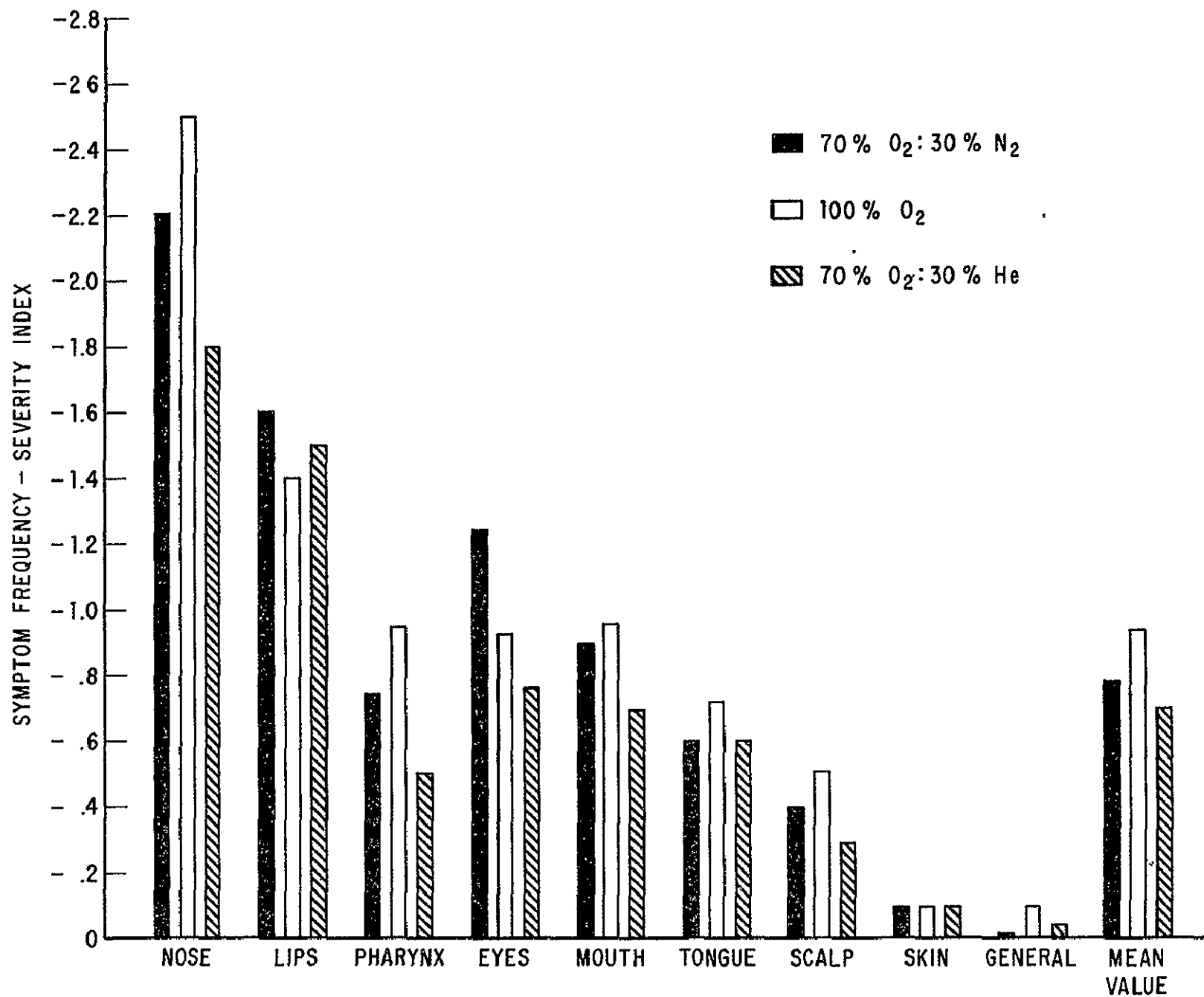
Fig. 42   Frequency-severity of signs related to the environment by
anatomical area involved; summary of all experiments.
Physician and subject evaluations are shown separately
together with a mean value for the two.
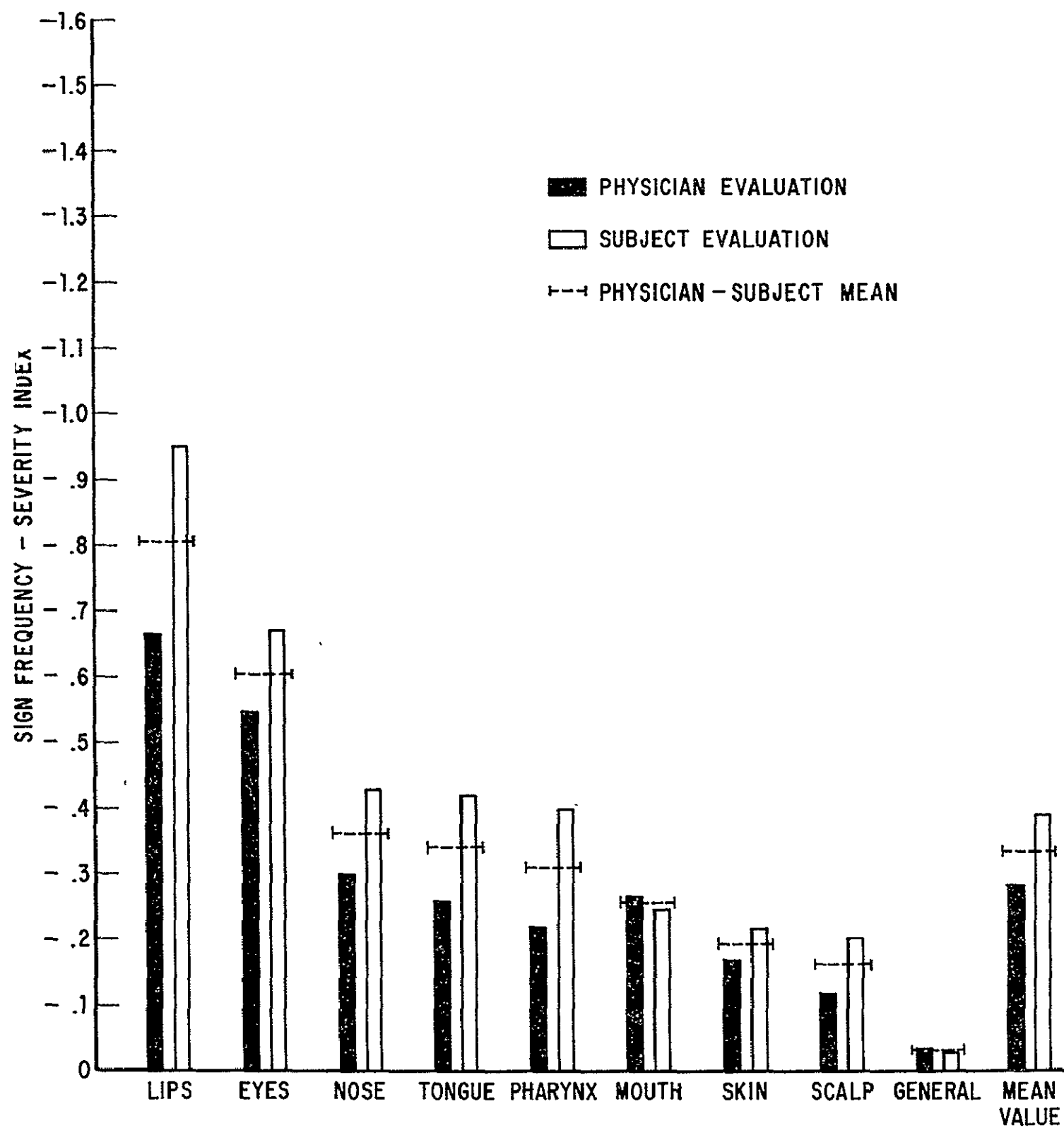
Fig. 43   Frequency-severity of signs related to the environment.
          Effect of P_B at 24° C. T_a (paired 24-hr and 48-hr experi-
          ments). Physician and subject evaluations are again shown
          separately.

-225-
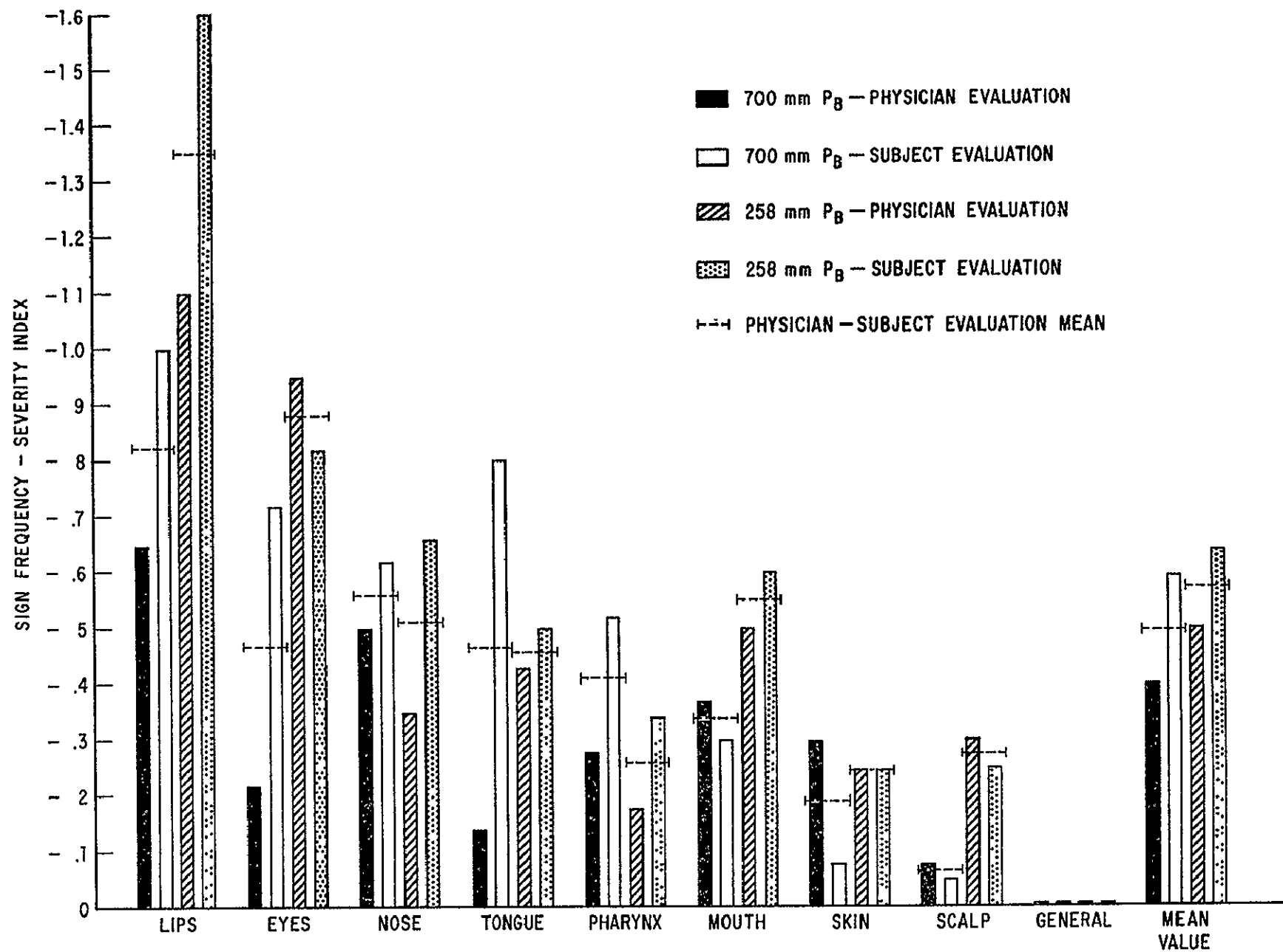
Fig. 44   Frequency-severity of signs related to the environment. Effect of P_{H_2O} at 24° C. T_a (matched 24-hr and 48-hr experiments).
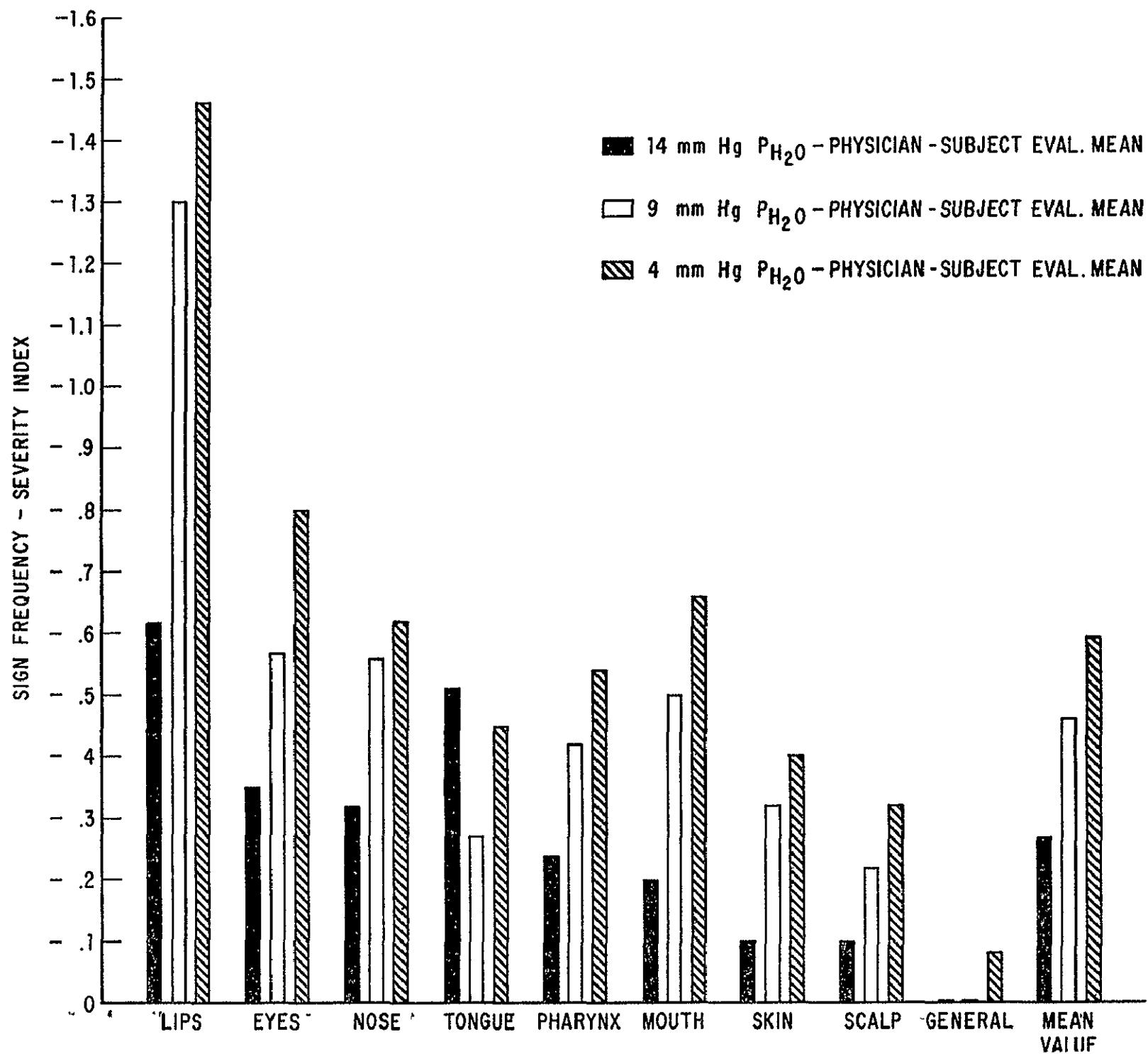
Fig. 45 Frequency-severity of signs related to the environment. Effects of T_a at 700 mm Hg P_B (matched 24-hr and 48-hr experiments).
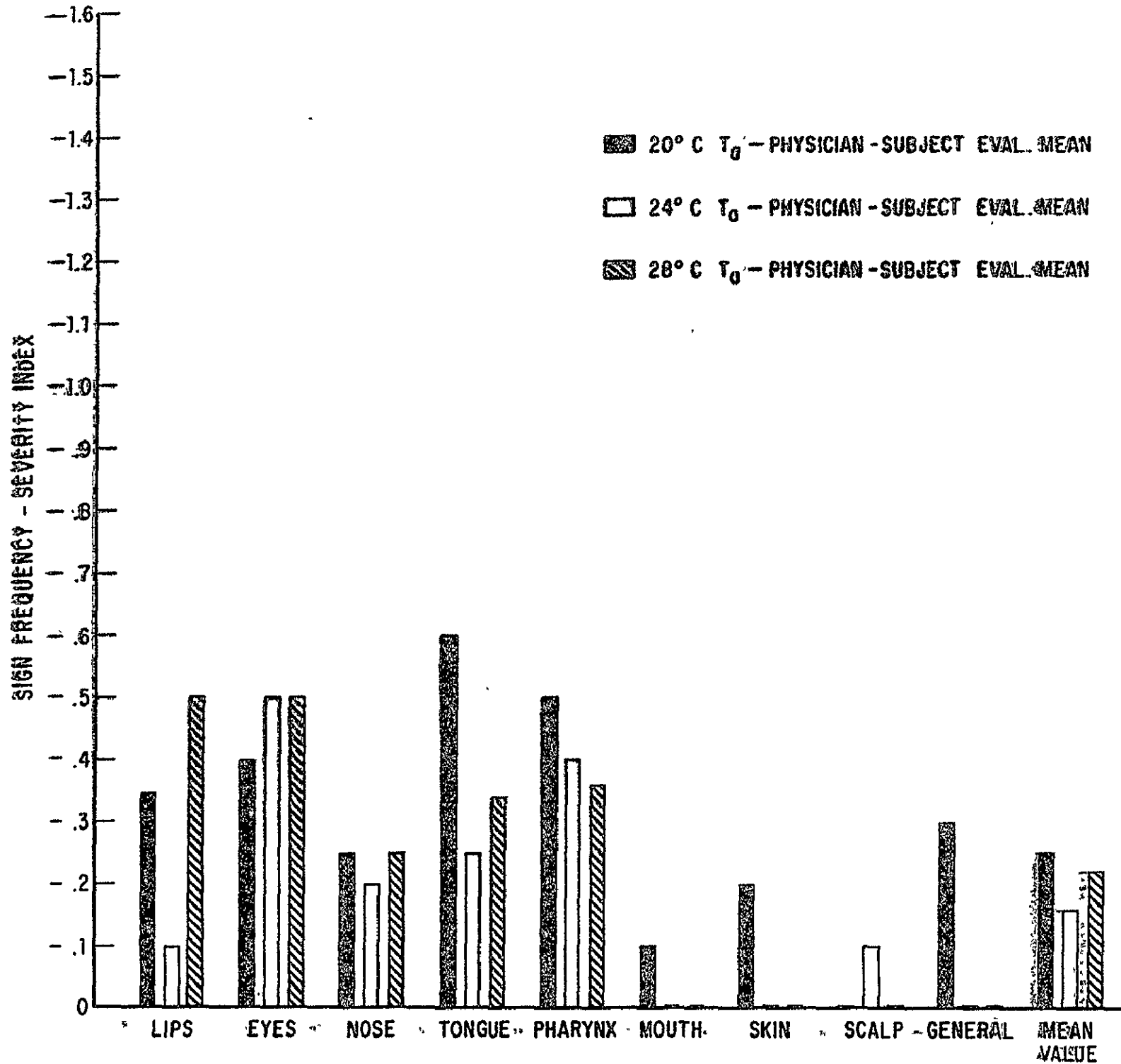
Fig. 46 Frequency-severity of signs related to the environment. Effect of gas composition at 258 mm Hg P_B and 24° C. T_a (matched experiments).
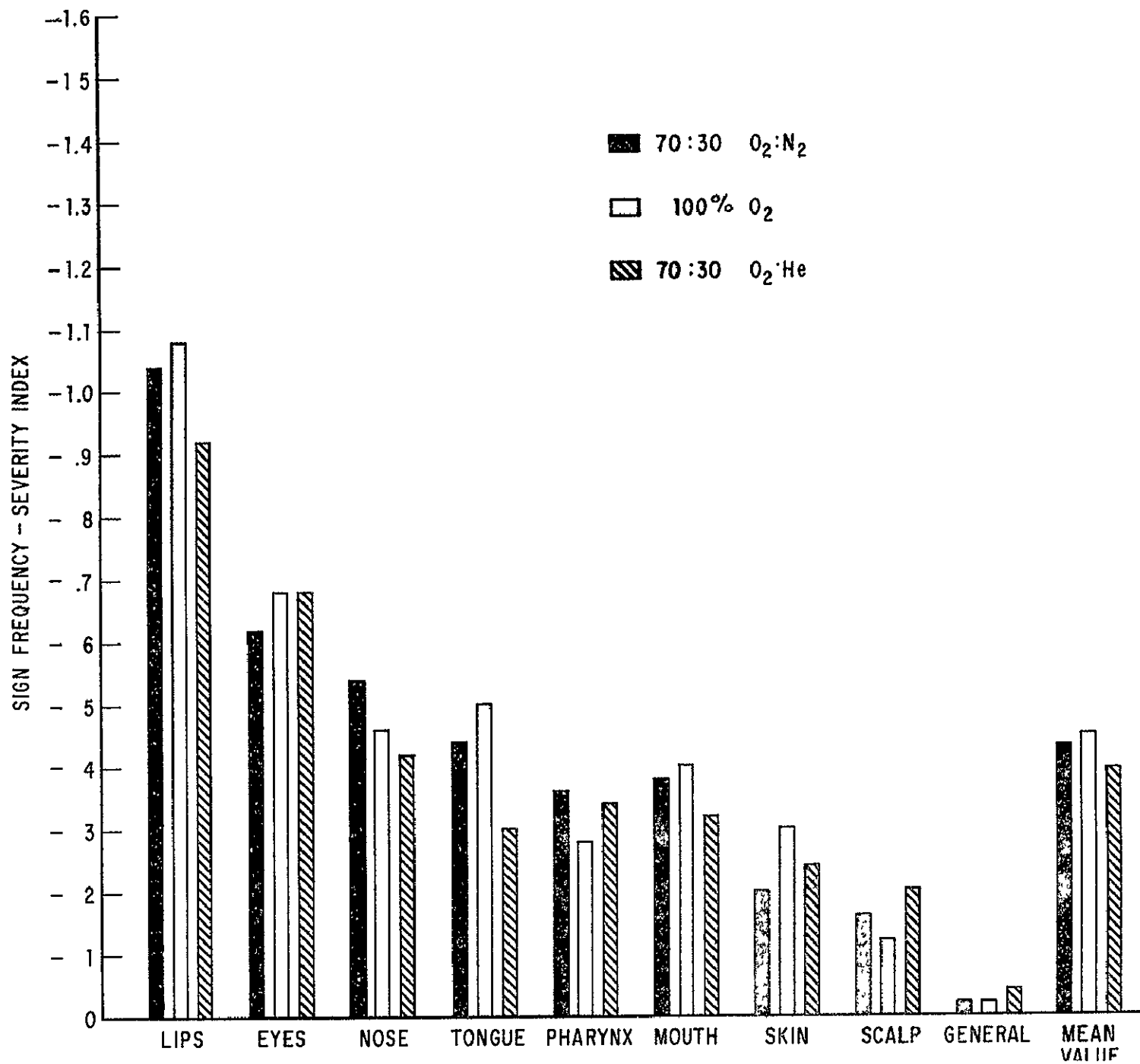
Fig. 47   Relationship of effective wall temperature (T_{ew}) to T_S
at varying P_B, G.C. and V. (Compare with Fig. 9.)
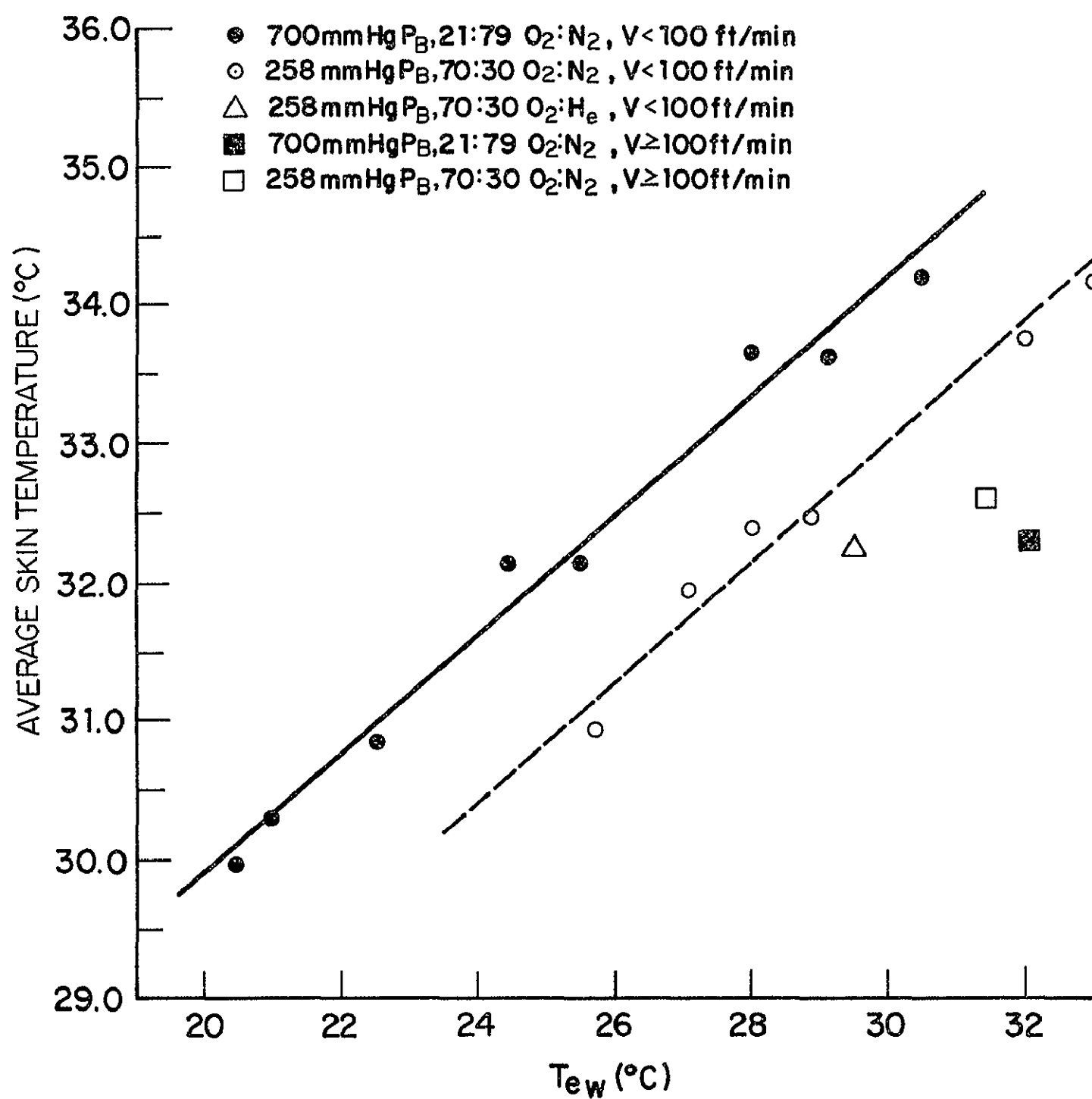
Fig. 48   Comparison of two high-IWL_S environments (B and C) with a
low IWL_S-environment (A). Increases in IWL_S, IWL_R, IWL_T,
and the Sign-Symptom Index for environments B and C are
expressed as a percent change over the comparable values
for environment A. Note the proportionate increases in
IWL_S, IWL_T, and the Sign-Symptom Index in environments
B and C.

(LOW IWL_S ENVIRONMENT)(HIGH IWL_S ENVIRONMENTS)

A. 700 mmHg P_B B. 258 mmHg P_B C. 258 mmHg P_B
14 mmHg P_{H_2O} 6.8 mmHg P_{H_2O} 4.8 mmHg P_{H_2O}
20°C T_a 28°C T_a 28°C T_a
50 ft/min V 150 ft/min V 50 ft/min V
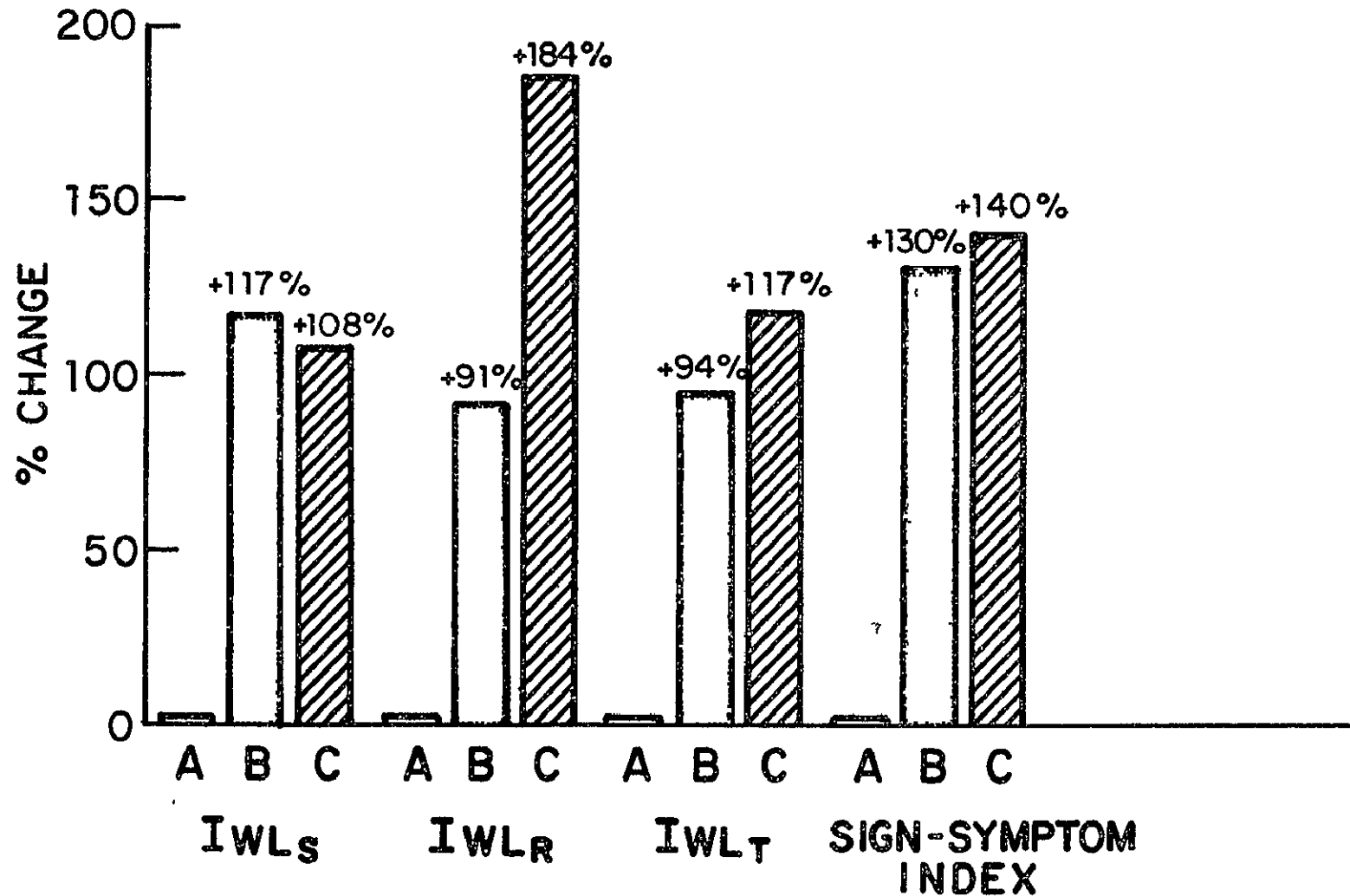
Fig. 49 Relationship of rates of skin insensible water loss to the Sign-Symptom Index. Both parameters are expressed as a percent increase over the baseline values. Note that the Sign-Symptom Index does not begin to increase rapidly until IWL_S has increased by more than 50% over baseline.